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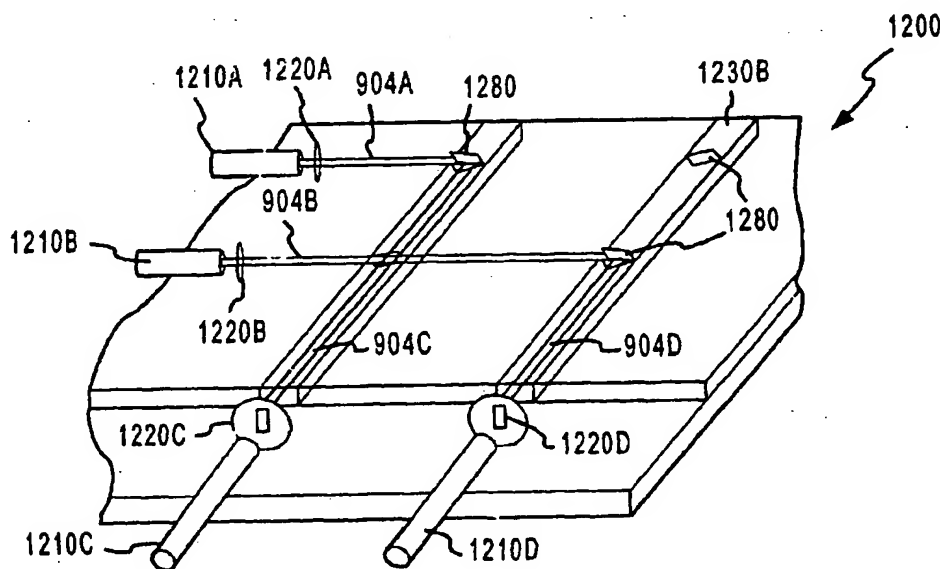
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(54) Title: **OPTICAL MEMS SWITCHING ARRAY WITH EMBEDDED BEAM-CONFINING CHANNELS AND METHOD OF OPERATING SAME**



(57) Abstract: A new optical switch device and method of operating such a device overcomes alignment problems through the use of an optical signal-confining channel that may be embedded so as to confine optical signals in a desired propagation path such that the optical signal's alignment with the output is secured. Small-angle mirrors may be used so as to direct the optical signal into the intended optical signal-confining channels so as to achieve the desired optical switching. The mirrors could be latching micro-mirrors or non-latching micro-mirrors. Such mirrors could be controlled by electrostatic actuation, thermal actuation or electromagnetic actuation, or any other technique.

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OPTICAL MEMS SWITCHING ARRAY WITH EMBEDDED BEAM-CONFINING CHANNELS AND METHOD OF OPERATING SAME

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certain rights to this invention.

FIELD OF THE INVENTION

10 The present disclosure relates to electronic and optical switches. More specifically,
the present disclosure describes latching micro-magnetic switches with low power
consumption and methods of formulating and operating micro-magnetic switches.
Furthermore, the present disclosure describes an optical switching array having embedded
beam-confining channels so as to minimize mis-alignment of light and attenuation of light,
15 along with associated methods.

BACKGROUND OF THE INVENTION

Switches are typically electrically-controlled two-state devices that open and close
contacts to effect operation of devices in an electrical or optical circuit. Relays, for example,
20 typically function as switches that activate or de-activate portions of electrical, optical or
other devices. Relays are commonly used in many applications including
telecommunications, radio frequency (RF) communications, portable electronics, consumer
and industrial electronics, aerospace, and other systems. More recently, optical switches
(also referred to as "optical relays" or simply "relays" herein) have been used to switch
25 optical signals (such as pulses of light traveling in fiber optics or other optical
communication systems) from one path to another.

Although the earliest relays were mechanical or solid-state devices, recent
developments in micro-electro-mechanical systems (MEMS) technologies and
microelectronics manufacturing have made micro-electrostatic and micro-magnetic relays
30 possible. Such micro-magnetic relays typically include an electromagnet that energizes an
armature to make or break an electrical contact. When the magnet is de-energized, a spring
or other mechanical force typically restores the armature to a quiescent position. Other
electrostatic relays use voltage differences between a movable cantilever and a fixed

electrode pad to generate electrostatic force that actuates an armature or cantilever. Other relays have used other actuation mechanisms, such as thermal actuation, shape memory alloy actuation, and the like. Such relays typically exhibit a number of marked disadvantages, however, in that they generally exhibit only a single stable output (i.e. the quiescent state) and they are not latching (i.e. they do not retain a constant output as power is removed from the relay). Moreover, the spring required by conventional micro-magnetic relays may degrade or break over time.

An example of a micro-magnetic relay is described in U.S. Patent No. 5,847,631 issued to Taylor et al. on December 8, 1998, the entirety of which is incorporated herein by reference. The relay disclosed in this reference includes a permanent magnet and an electromagnet for generating a magnetic field that intermittently opposes the field generated by the permanent magnet. Although this relay purports to be bi-stable, the relay requires consumption of power in the electromagnet to maintain at least one of the output states. Moreover, the power required to generate the opposing field would be significant, thus making the relay less desirable for use in space, portable electronics, and other applications that demand low power consumption.

With regard to optical switches, a further significant challenge relates to alignment of input laser light. Most conventional mirrors used in aligning laser light to an optical fiber or other component generally fall into one of two categories, referred to herein as "flip-up" mirrors or "vertical sliding mirrors". Before actuation, the "flip up" mirror typically lies flat so that incoming light is not affected by the mirror. After actuation, the mirror typically stands vertically to reflect the incoming laser beam by approximately 90 degrees. At the output of the relay, an optical fiber with a micro lens typically resides in a trench etched on a substrate to collect the laser beam. The mirror may be supported by an actuating arm (or arms) with micro hinges at the bottom to provide a rotation pivot. It can also be supported by flexure springs. Flip-up mirrors are typically actuated by various mechanisms (e.g. a scratch drive, comb drive, impact comb drive, sliding gear with comb drive, simple electrostatic force between mirror and sidewall, magnetic force, or the like).

Unlike the "flip up" mirrors which typically require rotation during actuation, a vertical sliding mirror typically uses a special translation to activate. Typically, the mirror sits vertically on top of a slide. When the mirror is actuated, it slides to a position predetermined by a stopper to intercept the laser beam path and reflects it by 90 degree. Vertical mirrors are typically made by an LIGA (Roentgen Lithographie Galvanik

Abformung: X-ray lithography, electrodeposition and molding) process or by deep reactive ion etching (DRIE), followed by a coating with reflective metal. The slope of the mirror may be on the order of about 1/1000 with the LIGA process. The surface smoothness may be on the order of about 5 nm with the DRIE process.

5 It frequently becomes extremely difficult to align a laser beam reflected by the vertical mirror to the output port in free space when the switch array size becomes large (e.g. on the order of 512x512). Assuming a chip size to be 5 cm, then the switch size needs to be about 5/512, or about 100 micrometers. Because designs typically require alignment accuracy on the order of about 0.01°, it becomes extremely difficult to achieve such
10 accuracy with standard microelectronics fabrication techniques. Active mirror fine-tuning can somewhat relieve the problem, but this tuning typically introduces other problems such as complication in fabrication and circuits, slower speed, etc. In addition to the alignment problems, the divergence of the laser beam may also become unacceptable when the array size becomes large (e.g. when the transmission distance exceeds about 1 cm). It is therefore
15 desirable to create an optical switch capable of meeting rigorous design specifications even in large switch fabrics.

BRIEF SUMMARY OF EXEMPLARY EMBODIMENTS

A new optical switch device and method of operating such a device overcomes
20 alignment problems through the use of an optical signal-confining channel that may be embedded so as to confine optical signals in a desired propagation path such that the optical signal's alignment with the output is secured. Small-angle mirrors may be used so as to direct the optical signal into the intended optical signal-confining channels so as to achieve the desired optical switching. The mirrors could be latching micro-mirrors or non-latching
25 micro-mirrors. Such mirrors could be controlled by electrostatic actuation, thermal actuation or electromagnetic actuation, or any other technique.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

The above and other features and advantages of the present invention are hereinafter
30 described in the following detailed description of illustrative embodiments to be read in conjunction with the accompanying drawing figures, wherein like reference numerals are used to identify the same or similar parts in the similar views, and:

Figures 1A and 1B are side and top views, respectively, of an exemplary embodiment of a switch;

Figures 2A-H are side views showing an exemplary technique for manufacturing a switch;

5 Figures 3A and 3B are side and top views, respectively, of a second exemplary embodiment of a switch;

Figure 3C is a perspective view of an exemplary cantilever suitable for use with the second exemplary embodiment of a switch;

10 Figure 3D is a perspective of an exemplary embodiment of a switch that includes sectionalized magnetically sensitive members;

Figure 3E is a side view of an exemplary cantilever that includes multiple magnetically sensitive layers;

Figures 4A and 4B are exemplary side and top views of a third exemplary embodiment of a latching relay;

15 Figures 4C and 4D are perspective views of exemplary cantilevers suitable for use with the third exemplary embodiment of a latching relay;

Figure 5 is a side view of a fourth exemplary embodiment of a latching relay;

Figures 6A and 6B are side and top views, respectively, of a fifth exemplary embodiment of a latching relay;

20 Figures 7 A and 7B are side and top views, respectively, of an exemplary "Type I" mirror;

Figures 8A and 8B are side and top views, respectively, of an exemplary "Type II" mirror in a horizontal orientation;

25 Figures 8C and 8D are side and top views, respectively, of an exemplary "Type II" mirror in a vertical orientation;

Figure 8E is a side view of an exemplary second embodiment of a reflecting mirror;

Figures 8F and 8G are top and side views, respectively, of an exemplary third embodiment of a reflector/mirror;

Figures 9A and 9B are side and top views of an exemplary switch in a first state;

30 Figures 10A and 10B are side and top views of an exemplary switch in a second state;

Figure 11 is a top view of an exemplary 5 x 5 optical switch;

Figure 12A is a perspective view of an exemplary optical cross switch array;

Figure 12B(a) and 12B(b) are side views of an exemplary optical signal-confining channel;

Figure 13 is an enlarged perspective view of an exemplary optical signal's path into and through an exemplary optical signal-confining channel;

5 Figure 14A and 14B are top and side views of a schematic diagram of an optical signal's path into and through an exemplary optical cross switch array with an exemplary optical signal-confining channel having optical mirrors only on the outer upper channel surface in a first state;

10 Figure 15A and 15B are top and side views of a schematic diagram of an optical signal's path into and through an exemplary optical cross switch array with an exemplary optical signal-confining channel having optical mirrors only on the outer upper channel surface in a second state;

15 Figure 16A and 16B are top and side views of a schematic diagram of an optical signal's path into and through an exemplary optical cross switch array with an optical signal-confining channel having optical mirrors on both outer upper channel and inner lower channel surfaces in a first state;

20 Figure 17A and 17B are top and side views of a schematic diagram of an optical signal's path into and through an exemplary optical cross switch array with an optical signal-confining channel having optical mirrors on both outer upper channel and inner lower channel surfaces in a second state;

Figure 18 is a perspective view of an exemplary optical cross switch array where optical signal-confining channel is used to input optical signal into optical cross switch array in a first state; and

25 Figure 19 is a perspective view of an exemplary optical cross switch array where optical signal-confining channel is used to input optical signal into optical cross switch array in a second state.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

30 It should be appreciated that the particular implementations shown and described herein are examples of the invention and are not intended to otherwise limit the scope of the present invention in any way. Indeed, for the sake of brevity, conventional electronics, manufacturing, MEMS technologies and other functional aspects of the systems (and components of the individual operating components of the systems) may not be described in

detail herein. Similarly, various control or actuation elements for different control mechanisms may not be shown in various drawing figures for simplicity. Furthermore, for purposes of brevity, the invention is frequently described herein as pertaining to a micro-electronically-machined relay for use in electrical or electronic systems. It should be appreciated that many other manufacturing techniques could be used to create the relays described herein, and that the techniques described herein could be used in mechanical relays, optical relays or any other switching device. Further, the techniques would be suitable for application in electrical systems, optical systems, consumer electronics, industrial electronics, wireless systems, space applications, or any other application. Moreover, it should be understood that the spatial descriptions (e.g. "above", "below", "up", "down", etc.) made herein are for purposes of illustration only, and that practical latching relays may be spatially arranged in any orientation or manner. Arrays of these relays can also be formed by connecting them in appropriate ways and with appropriate devices.

A Latching Switch

Figures 1A and 1B show side and top views, respectively, of a latching switch. With reference to Figures 1A and 1B, an exemplary latching relay 100 suitably includes a magnet 102, a substrate 104, an insulating layer 106 housing a conductor 114, a contact 108 and a cantilever 112 positioned above substrate by a staging layer 110.

Magnet 102 is any type of magnet such as a permanent magnet, an electromagnet, or any other type of magnet capable of generating a magnetic field H_0 134, as described more fully below. In an exemplary embodiment, magnet 102 is a Model 59-P09213T001 magnet available from the Dexter Magnetic Technologies corporation of Fremont, California, although of course other types of magnets could be used. Magnetic field 134 may be generated in any manner and with any magnitude, such as from about 1 Oersted to 10^4 Oersted or more. In the exemplary embodiment shown in Figure 1, magnetic field H_0 134 may be generated approximately parallel to the Z axis and with a magnitude on the order of about 370 Oersted, although other embodiments will use varying orientations and magnitudes for magnetic field 134. In various embodiments, a single magnet 102 may be used in conjunction with a number of relays 100 sharing a common substrate 104.

Substrate 104 is formed of any type of substrate material such as silicon, gallium arsenide, glass, plastic, metal or any other substrate material. In various embodiments, substrate 104 may be coated with an insulating material (such as an oxide) and planarized or

otherwise made flat. In various embodiments, a number of latching relays 100 may share a single substrate 104. Alternatively, other devices (such as transistors, diodes, or other electronic devices) could be formed upon substrate 104 along with one or more relays 100 using, for example, conventional integrated circuit manufacturing techniques. Alternatively, magnet 102 could be used as a substrate and the additional components discussed below could be formed directly on magnet 102. In such embodiments, a separate substrate 104 may not be required.

Insulating layer 106 is formed of any material such as oxide or another insulator such as a thin-film insulator. In an exemplary embodiment, insulating layer is formed of Probimide 7510 material. Insulating layer 106 suitably houses conductor 114. Conductor 114 is shown in Figures 1A and 1B to be a single conductor having two ends 126 and 128 arranged in a coil pattern. Alternate embodiments of conductor 114 use single or multiple conducting segments arranged in any suitable pattern such as a meander pattern, a serpentine pattern, a random pattern, or any other pattern. Conductor 114 is formed of any material capable of conducting electricity such as gold, silver, copper, aluminum, metal or the like. As conductor 114 conducts electricity, a magnetic field is generated around conductor 114 as discussed more fully below.

Cantilever 112 is any armature, extension, outcropping or member that is capable of being affected by magnetic force. In the embodiment shown in Figure 1A, cantilever 112 suitably includes a magnetic layer 118 and a conducting layer 120. Magnetic layer 118 may be formulated of permalloy (such as NiFe alloy) or any other magnetically sensitive material. Conducting layer 120 may be formulated of gold, silver, copper, aluminum, metal or any other conducting material. In various embodiments, cantilever 112 exhibits two states corresponding to whether relay 100 is "open" or "closed", as described more fully below. In many embodiments, relay 100 is said to be "closed" when a conducting layer 120 connects staging layer 110 to contact 108. Conversely, the relay may be said to be "open" when cantilever 112 is not in electrical contact with contact 108. Because cantilever 112 may physically move in and out of contact with contact 108, various embodiments of cantilever 112 will be made flexible so that cantilever 112 can bend as appropriate. Flexibility may be created by varying the thickness of the cantilever (or its various component layers), by patterning or otherwise making holes or cuts in the cantilever, or by using increasingly flexible materials. Alternatively, cantilever 112 can be made into a "hinged" arrangement such as that described below in conjunction with Figure 3. Although of course the

dimensions of cantilever 112 may vary dramatically from implementation to implementation, an exemplary cantilever 112 suitable for use in a micro-magnetic relay 100 may be on the order of 10-1000 microns in length, 1-40 microns in thickness, and 2-600 microns in width. For example, an exemplary cantilever in accordance with the embodiment
5 shown in Figure 1 may have dimensions of about 600 microns x 10 microns x 50 microns, or 1000 microns x 600 microns x 25 microns, or any other suitable dimensions.

Contact 108 and staging layer 110 are placed on insulating layer 106, as appropriate. In various embodiments, staging layer 110 supports cantilever 112 above insulating layer 106, creating a gap 116 that may be vacuum or may become filled with air or another gas or
10 liquid such as oil. Although the size of gap 116 varies widely with different implementations, an exemplary gap 116 may be on the order of 1-100 microns, such as about 20 microns. Contact 108 may receive cantilever 112 when relay 100 is in a closed state, as described below. Contact 108 and staging layer 110 may be formed of any conducting material such as gold, gold alloy, silver, copper, aluminum, metal or the like. In various
15 embodiments, contact 108 and staging layer 110 are formed of similar conducting materials, and the relay is considered to be "closed" when cantilever 112 completes a circuit between staging layer 110 and contact 108. Other embodiments use different formulations for contact 108 and staging layer 110, such as those discussed below in conjunction with Figures 3 and 4. In certain embodiments wherein cantilever 112 does not conduct electricity, staging
20 layer 110 may be formulated of non-conducting material such as Probimide material, oxide, or any other material. Additionally, alternate embodiments may not require staging layer 110 if cantilever 112 is otherwise supported above insulating layer 106.

Principle of Operation

25 In a broad aspect of the invention, magnet 102 generates a magnetic field H_0 126 that induces a magnetization (m) in cantilever 112. The magnetization suitably creates a torque on cantilever 112 that forces cantilever 112 toward contact 108 or away from contact 108, depending upon the direction of the magnetization, thus placing relay 100 into an open or closed state. The direction of magnetization in cantilever 112 may be adjusted by a second
30 magnetic field generated by conductor 114 as appropriate, and as described more fully below.

With continued reference to Figures 1A and 1B, magnetic field H_0 134 may be applied by magnet 102 primarily in the direction parallel to the Z-axis such that the field is

perpendicular to the primary dimension (e.g. the length) of cantilever 112. Magnetic field 134 suitably induces a magnetization in cantilever 112, which may be made of soft magnetic material. Because of the geometry of cantilever 112, the magnetization in cantilever 112 suitably aligns along the long axis of the cantilever, which is the length of cantilever 112 (parallel to the X-axis) in Figure 1.

The orientation of the magnetization in cantilever 112 is suitably dependent upon the angle (α) between the applied magnetic field 134 and the long axis of cantilever 112. Specifically, when the angle (α) is less than 90 degrees, the magnetic moment (m) in cantilever 112 points from end 130 of cantilever 112 toward end 132. The interaction between the magnetic moment and magnetic field H_0 134 thus creates a torque in a counter-clockwise direction about end 130 of cantilever 112 that moves end 132 upward, as appropriate, thus opening the circuit between staging layer 110 and contact 108. Conversely, when the angle (α) is greater than 90 degrees, the magnetic moment (m) in cantilever 112 points from end 132 toward end 130, creating a clockwise torque about end 130. The clockwise torque moves end 132 downward to complete the circuit between staging layer 110 and contact 108. Because the magnetization (m) of cantilever 112 does not change unless the angle (α) between the long axis of cantilever 112 and the applied magnetic field 134 changes, the applied torque will remain until an external perturbation is applied. Elastic torque of the cantilever or a stopper (such as the contact) balances the applied magnetic torque, and thus relay 100 exhibits two stable states corresponding to the upward and downward positions of cantilever 112 (and therefore to the open and closed states, respectively, of relay 100).

Switching may be accomplished by any suitable technique that reverses the direction of the cantilever's magnetic dipole moment. In an exemplary embodiment, switching may be accomplished by generating a second magnetic field that has a component along the long axis of cantilever 112 that is strong enough to affect the magnetization (m) of cantilever 112. In the embodiment shown in Figure 1, the relevant component of the second magnetic field is the component of the field along the X-axis. Because the strength of the second magnetic field along the long axis of cantilever 112 is of primary concern, the overall magnitude of the second magnetic field is typically significantly less than the magnitude of magnetic field 134 (although of course fields of any strength could be used in various embodiments). An exemplary second magnetic field may be on the order of 20 Oersted, although of course stronger or weaker fields could be used in other embodiments.

The second magnetic field may be generated through, for example, a magnet such as an electronically-controlled electromagnet. Alternatively, the second magnetic field may be generated by passing a current through conductor 114. As current passes through conductor 114, a magnetic field is produced in accordance with a "right-hand rule". For example, a current flowing from point 126 to point 128 on conductor 114 (Figure 1B) typically generates a magnetic field "into" the center of the coil shown, corresponding to field arrows 122 in Figure 1A. Conversely, a current flowing from point 128 to point 126 in Figure 1 generates a magnetic field flowing "out" of the center of the coil shown, corresponding to dashed field arrows 124 in Figure 1A. The magnetic field may loop around the conductor 114 in a manner shown also in Figure 1A, imposing a horizontal (X) component of the magnetic field on the cantilever 112.

By varying the direction of the current or current pulse flowing in conductor 114, then, the direction of the second magnetic field can be altered as desired. By altering the direction of the second magnetic field, the magnetization of cantilever 112 may be affected and relay 100 may be suitably switched open or closed. When the second magnetic field is in the direction of field arrows 122, for example, the magnetization of cantilever 112 will point toward end 130. This magnetization creates a clockwise torque about end 130 that places cantilever 112 in a "down" state that suitably closes relay 100. Conversely, when the second magnetic field is in the direction of dashed field arrows 124, the magnetization of cantilever 112 points toward end 132, and a counter-clockwise torque is produced that places cantilever 112 in an "up" state that suitably opens relay 100. Hence, the "up" or "down" state of cantilever 112 (and hence the "open" or "closed" state of relay 100) may be adjusted by controlling the current flowing through conductor 114. Further, since the magnetization of cantilever 112 remains constant without external perturbation, the second magnetic field may be applied in "pulses" or otherwise intermittently as required to switch the relay. When the relay does not require a change of state, power to conductor 114 may be eliminated, thus creating a bi-stable latching relay 100 without power consumption in quiescent states. Such a relay is well suited for applications in space, aeronautics, portable electronics, and the like.

30 Manufacturing a Latching Relay

Figure 2 includes a number of side views showing an exemplary technique for manufacturing a latching relay 100. It will be understood that the process disclosed herein is

provided solely as an example of one of the many techniques that could be used to formulate a latching relay 100.

An exemplary fabrication process suitably begins by providing a substrate 102, which may require an optional insulating layer. As discussed above, any substrate material could be used to create a latching relay 100, so the insulating layer will not be necessary if, for example, an insulating substrate is used. In embodiments that include an insulating layer, the layer may be a layer of silicon dioxide (SiO_2) or other insulating material that may be on the order of 1000 angstroms in thickness. Again, the material chosen for the insulating material and the thickness of the layer may vary according to the particular implementation.

With reference to Figure 2A, conductor 114 is suitably formed on substrate 104. Conductor 114 may be formed by any technique such as deposition (such as e-beam deposition), evaporation, electroplating or electroless plating, or the like. In various embodiments, conductor 114 is formed in a coil pattern similar to that shown in Figure 1. Alternatively, conductor 114 is formed in a line, serpentine, circular, meander, random or other pattern. An insulating layer 106 may be spun or otherwise applied to substrate 104 and conductor 114 as shown in Figure 2B. Insulating layer 106 may be applied as a layer of photoresist, silicon dioxide, Probimide-7510 material, or any other insulating material that is capable of electrically isolating the top devices. Though only one conductor layer is shown in Figure 2A, repeated multi-layers of conducting material may be added. These multiple layers may be connected in serial (or parallel or otherwise) through vias or other techniques to increase the strength of the magnetic field produced by a given current. In various embodiments, the surface of the insulating material is planarized through any technique such as chemical-mechanical planarization (CMP).

Contact pads 108 and 110 may be formed on insulating layer 106 through any technique such as photolithography, etching, or the like (Figure 2C). Pads 108 and 110 may be formed by depositing one or more layers of conductive material on insulating layer 106 and then patterning the pads by wet etching, for example. In an exemplary embodiment, pads 108 and 110 suitably include a first layer of chromium or titanium (to improve adhesion to insulating layer 106) and a second layer of gold, silver, copper, aluminum, or another conducting material. Additional metal layers may be added to the contacts by electroplating or electroless plating methods to improve the contact reliability and lower the resistance.

With reference to Figure 2D, the contact pads 108 and 110 may be suitably covered with a layer of photoresist, aluminum, copper, or other material to form sacrificial layer 202.

An opening 206 in sacrificial layer 202 over the cantilever base areas may be defined by photolithography, etching, or another process. Cantilever 112 may then be formed by depositing, sputtering or otherwise placing one or more layers of material on top of sacrificial layer 202 and extending over the opening 206, as shown in Figure 2E. In an
5 exemplary embodiment, a base layer 204 of chromium or another metal may be placed on sacrificial layer 202 to improve adhesion, and one or more conducting layers 120 may be formed as well. Layers 204 and 120 may be formed by, for example, deposition followed by chemical or mechanical etching. Layer 120 may be thickened by adding another conductor layer (such as gold, gold alloy, etc.) by electroplating or electroless plating methods.
10 Cantilever 112 is further formed by electroplating or otherwise placing a layer 118 of permalloy (such as NiFe permalloy) on top of conducting layer 120, as shown in Figure 2F. The thickness of the permalloy layer 118 may be controlled by varying the plating current and time of electroplating. Electroplating at 0.02 amperes per square centimeters for a period of 60 minutes, for example, may result in an exemplary permalloy layer thickness of
15 about 20 microns. In various embodiments, an additional permalloy layer 306 (shown in Figure 3) may be electroplated on top of cantilever 112 to increase the responsiveness of cantilever 112 to magnetic fields.

With reference to Figure 2G, sacrificial layer 202 may be removed by, for example, wet or dry (i.e. oxygen plasma) releasing techniques to create gap 116 between cantilever
20 112 and insulating layer 106. In various embodiments, adhesion layer 204 is removed using a suitable etching or equivalent removal technique to form relay 100 (Figure 2H). Relay 100 may then be diced, packaged with magnet 102 (shown in Figure 1), or otherwise processed as appropriate. It should be understood that the permanent magnet 102 can alternatively be fabricated directly on the substrate, placed on top of the cantilever, or the
25 coil and the cantilever can be fabricated directly on a permanent magnet substrate.

Alternate Embodiments of Latching Relays

Figures 3 and 4 disclose alternate embodiments of latching relays 100. Figures 3A and 3B show side and top views, respectively, of an alternate embodiment of a latching relay
30 that includes a hinged cantilever 112. The perspective of Figures 3A and 3B is rotated 90 degrees in the X-Y plane from the perspective shown in Figures 1A and 1B to better show the detail of the hinged cantilever. With reference to Figures 3A and 3B, a hinged cantilever 112 suitably includes one or more strings 302 and 304 that support a magnetically sensitive

member 306 above insulating layer 106. Member 306 may be relatively thick (on the order of about 50 microns) compared to strings 302 and 304, which may be formed of conductive material. As with the relays 100 discussed above in conjunction with Figure 1, relays 100 with hinged cantilevers may be responsive to magnetic fields such as those generated by magnet 102 and conductor 114. In various embodiments, one or both of strings 302 and 304 are in electrical communication with contact pad 108 when the relay is in a "closed" state. Of course, any number of strings could be used. For example, a single string could be formulated to support the entire weight of member 306. Additionally, the strings may be located at any point on member 306. Although Figure 3 shows strings 302 and 304 near the center of member 306, the strings could be located near the end of member 306 toward contact 108 to increase the torque produced by magnet 102, for example.

Figure 3C is a perspective view of an exemplary cantilever 112 suitable for use with the embodiments shown in Figures 3A and 3B, as well as other embodiments. Cantilever 112 suitably includes member 306 coupled to conducting layer 120. Holes 310 and/or 312 may be formed in conducting layer 120 to improve flexibility of cantilever 112, and optional contact bumps 308 may be formed on the surface of conducting layer 120 to come into contact with contact 108. Strings 302 and 304 (not shown in Figure 3C) may be affixed or otherwise formed on cantilever 112 at any position (such as in the center of conducting layer 120 or at either end of conducting layer 120) as appropriate. Alternatively, the strings may be formed of non-conducting materials and cantilever 112 may provide a conducting path between two separate conductors touched simultaneously by the cantilever in the closed state, as discussed below.

It has been observed that certain switches that include relatively wide magnetically sensitive members 306 may exhibit reduced magnetization because of the relatively large ratio of the width-to-length of cantilever 112. Moreover, the increased width may lead to increased magnetization along the width of cantilever 112, which may result in twisting of the cantilever and degraded contact between cantilever 112 and contact 108. Figure 3D is a perspective view of a switch that includes sectionalized magnetically sensitive members 306A, 306B, 306C and 306D. To improve the magnetization along the length of cantilever 112, the magnetically sensitive member 306 may be sectionalized so that the magnetization of each member 306A-D is maximized along the length of the member instead of the width. Sectionalization may be accomplished by separately forming (e.g. electroplating) each member 306A-D on conducting layer 120, for example, or by etching (or otherwise forming)

gaps in a single electroplated layer 306. Of course any number of magnetically sensitive sections 306A-D could be used with various embodiments, and the size of each section will vary from embodiment to embodiment. For example, various exemplary cantilevers 112 could be fashioned with four members 306A-D of about 1000 x 600 x 25 micrometers, with
5 eight members of about 1000 x 50 x 25 micrometers (spaced about 25 micrometers apart), with fifteen members of about 1000 x 20 x 25 micrometers (spaced about 25 micrometers apart), or with any number of members having any dimensions. In various embodiments, interlinks of magnetic material, metal or any other material may be added between the members 306A-D to strengthen cantilever 112. Figure 3E is a schematic of a cantilever 112
10 that has been formed with multiple layers. In an exemplary embodiment, cantilever 112 includes alternating layers of magnetic material 118 (such as permalloy) and conducting material 120, as shown in Figure 3E, although of course other materials could be used in place of or in addition to the materials shown. Multi-layered cantilevers may be formed by sputtering, depositing, or otherwise forming multiple layers as discussed, for example, in
15 connection with Figures 2E and 2F above, or through any other technique. Multi-layered cantilevers may also be sectionalized, as described above, and may be used in conjunction with any of the various embodiments of the invention.

Figures 4A and 4B are side and top views, respectively, of an alternate embodiment of a latching relay 100. As shown in the Figure, various embodiments of cantilever 112 may
20 not directly conduct electricity from staging layer 110 to contact 108. In such embodiments, a conducting element 402 may be attached to cantilever 112 to suitably provide electrical contact between contacts 108 and 408 when relay 100 is in a "closed" state. Figures 4C and 4D are perspective views of alternate exemplary embodiments of cantilever 112. In such
25 embodiments, cantilever 112 may include a magnetically sensitive portion 118 separated from a conducting portion 402 by an insulating layer 410, which may be a dielectric insulator, for example. Optional contact bumps 308 may also be formed on conducting portion 402 as shown. When cantilever 112 is in a state corresponding to the "closed" state of relay 100, current may follow the path shown by arrows 412 between contact pads 108 and 408, as appropriate.

30 Figure 5 is a side view of an alternate exemplary embodiment of relay 100. With reference to Figure 5, a relay 100 may include a magnet 102, a substrate 104 and a cantilever 112 as described above (for example in conjunction with Figure 1). In place of (or in addition to) conductor 114 formed on substrate 104, however, conductor 114 may be formed

on a second substrate 504, as shown. Second substrate 504 may be any type of substrate such as plastic, glass, silicon, or the like. As with the embodiments described above, conductor 114 may be coated with an insulating layer 506, as appropriate. To create a relay 100, the various components may be formed on substrates 104 and 504, and then the
5 substrates may be aligned and positioned as appropriate. The two substrates 104 and 504 (and the various components formed thereon) may be separated from each other by spacers such as spacers 510 and 512 in Figure 5, which may be formed of any material.

With continued reference to Figure 5, contact 108 may be formed on insulating layer 106, as described above. Alternatively, contact 508 may be formed on second substrate 504,
10 as shown in Figure 5 (of course cantilever 112 may be reformulated such that a conducting portion of cantilever 112 comes into contact with contact 508). In other embodiments, contacts 108 and 508 may both be provided such that relay 100 is in a first state when cantilever 112 is in contact with contact 108, a second state when cantilever 112 is in contact with contact 508, and/or a third state when cantilever 112 is in contact with neither contact
15 108 nor contact 508. Of course the general layout of relay 100 shown in Figure 5 could be combined with any of the techniques and layouts described above to create new embodiments of relay 100.

Figures 6A and 6B are side and top views, respectively, of an alternate embodiment of a latching relay 100. With reference now to Figures 6A and 6B, various embodiments of
20 relay 100 may use electrostatic actuation to switch the state of cantilever 112 instead of magnetic energy generated by conductor 114. In such embodiments, one or more switching electrodes 602 and 604 may be deposited or otherwise fashioned on insulating layer 106. Electrodes 602 and 604 may be formed of metal or another conducting material, and may be electrically coupled to leads, wires or other connecting devices (not shown) to create an
25 electric potential between either of the electrodes and cantilever 112.

Although Figures 6A and 6B show a center-hinged type cantilever 112, electrodes 602 and 604 and/or the principle of electrostatic actuation may be included in any of the relays or switches described herein in place of (or in addition to) the magnetic actuation produced by conductor 114. In various embodiments, electrodes 602 and 604 are suitably
30 positioned with respect to cantilever 112 such that electrostatic forces generated by the two electrodes have opposing effects on cantilever 112. In the center-hinged embodiment shown in Figures 6A and 6B, for example, electrodes 602 and 604 may be positioned on either side of hinge 110 so that a voltage difference between electrode 602 and cantilever 112 "pushes"

cantilever 112 into an "open" state. Conversely, a voltage difference between electrode 604 and cantilever 112 may "pull" cantilever 112 into a "closed" state whereby cantilever 112 is in contact with contact 108. In such embodiments, the state of cantilever 112 may be held by the magnetic field generated by permanent magnet 102, and a bistable switch may result.

5 The relay may be switched between stable states by providing an electric potential to the appropriate electrode to attract cantilever 112 as appropriate. In an exemplary relay 100, a hinged type cantilever 112 having dimensions of about 1000 x 200 x 20 micrometers and a supporting torsion string 110 with dimensions of 280 x 20 x 3 micrometers may require a voltage of about 37 volts, when the overlap area between the cantilever and electrode is on
10 the order of 200 x 400 square micrometers or so, to switch cantilever 112 in a permanent external magnetic field of about 200 Oersted. Again, switches or relays can be formulated with any dimensions or architectures, and the voltage required to switch between states will suitably vary from implementation to implementation. In particular, the electrostatic switching technique using electrodes 602 and 604 can be incorporated into any of the relays
15 discussed above, or any of the switches described herein. Advantages of using electrostatic switching over magnetic switching include reduced power consumption and ease in manufacturing, since electrodes 602 and 604 can be very thin (e.g. on the order of about a hundred angstroms to about 0.5 micrometers thick). Moreover, electrostatic switches may be made to be smaller than some corresponding magnetic switches, thus reducing the overall
20 size of the switching device. Switching control may be provided by a control device such as a microcontroller, microprocessor, application specific integrated circuit (ASIC), logic circuit, analog or digital control circuit, or the like. In an exemplary embodiment, a controller provides control signals in the form of electrical signals to electrodes 602 and 604 to create voltage differences as appropriate.

25 It will be understood that many other embodiments of the various relays could be formulated without departing from the scope of the invention. For example, a double-throw relay could be created by adding an additional contact 108 that comes into contact with cantilever 112 when the cantilever is in its open state. Similarly, various topographies and geometries of relay 100 could be formulated by varying the layout of the various
30 components (such as pads 108 and 110 and cantilever 112).

Optical Switches

The mechanisms, principles and techniques described above in conjunction with electrical relays may also be used to create optical switches suitable for use in communications or other optical systems. In various embodiments of an optical switch, the magnetically sensitive portion of cantilever 112 may be affixed to a mirror or other material that reflects light. As the cantilever is switched from an "open" state to a "closed" state, the reflecting surface is exposed or hidden from an optical signal such that the signal is reflected or absorbed as appropriate, and as described more fully below.

Figures 7A and 7B are side and top views, respectively, of an exemplary optical mirror 700 (referred to herein as a "Type I" mirror). Like the electrical switches described above, a cantilever 112 is suitably positioned over insulating layer 106 by a support string, hinge or other spacer 110. Cantilever 112 may be formed of soft magnetic material 132 (as discussed above), and may have a reflective coating 702 (such as aluminum or gold) deposited, sputtered or otherwise placed on the magnetic material. One or more optional stoppers 704 may be positioned on insulating layer 106, as appropriate, to receive and position cantilever 112 as required. Stoppers 704 may be formed of any suitable material such as etched silicon, metal, or polyimide. In various embodiments, support string 110 supports rotation of cantilever 112 into an "up" state and a "down" state, as appropriate. When cantilever 112 is in an "up" state, for example, cantilever 112 may be rotated counter-clockwise about string 110 until end 742 of cantilever 132 contacts stopper 704L. In an exemplary "down" state, cantilever 112 may be rotated clockwise about string 110 such that the end 740 of cantilever 112 contacts stopper 740R. When the right end of 132 touches the bottom stopper 704, it is in the "down". By design, the supporting string 110 may be placed closer to end 742 of cantilever 112 such that cantilever 112 may be tilted to a larger angle in the "up" position than in the "down" position. Of course, support string 110 may also be placed approximately equidistant from the ends of cantilever 112, or such that the "down" position creates a larger angle, and many orientations could be formulated in other embodiments of the invention.

Operation of optical mirror 700 may be similar to the operation of the electrical switches 100 discussed above. In various exemplary embodiments, latching and switching are accomplished by inducing a magnetic torque in cantilever 112 with conductor 114 (as shown in Figure 7) or optional electrodes (as discussed above in connection with Figure 6).

Cantilever 112 may be stably maintained in either the "up" or "down" state through a field generated by magnet 102, as described above.

Figures 8A through 8G show various views and states of a second type of optical mirror 800 (referred to herein as a "Type II" mirror or "reflector"). Although these devices are primarily described herein as pertaining to reflective devices used with switches or relays, the principles and structures described herein could be used to create any sort of actuator (reflecting or non-reflecting) that may be used in any application.

With reference to Figures 8A and 8B, an optical mirror 800 may include a cantilever 112 that includes a magnetically sensitive portion 132. Cantilever 112 may also include a reflective portion 804 with a reflective coating on either or both sides. In an exemplary embodiment, reflective portion 804 has a reflective coating deposited or otherwise placed on face 802, as shown in Figure 8A. One or more stoppers 704 may also be placed on insulating layer 106 as required to position or elevate cantilever 112 as appropriate, and a support, string or hinge 110 (not shown in Figures 8A and 8C) may rotably fix cantilever 112 above substrate 104.

In an exemplary embodiment, string 110 supports ninety degrees of rotation between two states of cantilever 112 (plus or minus some correction for errors in manufacturing and the like). In the embodiment shown in Figures 8A and 8B, cantilever 112 is positioned into an "up" state by magnet 102 (not shown) to be approximately parallel to the surface of substrate 104. The "up" position may be useful when it is necessary to have a clear path for an optical beam to directly pass the Type II mirror without reflection, for example. A second "down" state of mirror 800 is shown in Figures 8C and 8D. Mirror 800 may be placed in the "down" state, for example, by magnet 102 (not shown) (In principle, the magnet can hold the cantilever to either of the two stable states) and/or by allowing gravity to pull the magnetically sensitive portion 132 of cantilever 112 away from the "up" position. It will be appreciated that a permanent magnet 102 and a conductor 114 may not be required for each embodiment of mirror 800, since other forces (such as force applied by optional buckling structures on stopper 704) may maintain cantilever 112 in the "down" position without requiring external forces. In many embodiments, a temporary magnetic field may be provided while the reflective coating is applied to cantilever 112 during manufacturing, and removed thereafter. In still other embodiments of mirror 800, hinge 110 and magnetically sensitive portion 132 may be eliminated and reflective portion 804 may be rigidly fixed to substrate 102 or insulating layer 104.

With reference now to Figure 8E, an alternate embodiment of a reflector 800 suitably includes a cantilever 112 and a torsion bar hinge or other anchor 870 that may be affixed to a substrate 104. A coil or other conductor 114 may also be provided, or an electrode capable of providing electrostatic attraction to cantilever 112 may be provided in an alternate embodiment. Cantilever 112 may be magnetically sensitive, as described above, and may have one or more reflective surfaces, as described above. Torsion bar hinge 870 may be implemented as one or more hinges, as described above in connection with other embodiments of switches or relays. In various embodiments, the torsion bar hinges may be located at or near the end of cantilever 112 and may be fashioned to be relatively thin and/or long with respect to cantilever 112 such that large rotational deflections of cantilever 112 may take place without significant mechanical torque. Moreover, the direction of the external magnetic field (H_0) 134 applied to reflector 800 may be placed at an angle (γ) relative to a perpendicular (Z) drawn from the face of substrate 104. In the exemplary embodiment shown in Figure 8E, for example, γ is selected to be about 45 degrees, although other embodiments may use other angles.

The direction of magnetic field 134 suitably creates two stable positions for cantilever 112, corresponding to an "up" state and a "down" state (cantilever 112 is shown between the two states in Figure 8E). In various embodiments, cantilever 112 may be aligned approximately perpendicular to substrate 104 in the "up" state, and approximately parallel to substrate 103 in the "down" state. A physical stopper (not shown in Figure 8E) may be provided to maintain cantilever 112 in the desired position for the "up" and/or "down" states.

In various embodiments, a magnetic field with a magnitude of about $\chi H_0 \sin(\gamma + \phi)$ Oersted or so may be provided by conductor 114 to switch cantilever 112 between states, where " χ " is the magnetic susceptibility of cantilever 112 and " ϕ " is the angle between cantilever 112 in the "down" state and the horizontal axis (X). A field of this magnitude may suitably re-align the magnetization vector of cantilever 112, as appropriate, similar to the switching techniques discussed above, so that cantilever 112 switches between two stable states. Because the field generated by conductor 114 may be relatively weak compared to the external field 134, field 134 may be designed to be large enough to actuate device 800 but not so strong that the field generated by conductor 114 cannot reverse the magnetization vector of cantilever 112. In an exemplary embodiment, field 134 may be designed to be on the order of about 200 Oersted, although of course other field strengths could be used. The

reflector 800 described herein may exhibit approximately 90 degrees or more of rotability, and consequently may have wide application beyond relays or optical switches. For example, reflectors 800 having relatively high degrees of rotability may be useful for optical projection or switch systems.

5 With reference now to Figures 8F and 8G, a third embodiment of a reflector 800 that may be used to rotate through 90 or more degrees suitably includes a conductor 114 placed on cantilever 112, which may be hingably connected to substrate 104 by a hinge 870 (shown as two torsion hinges 870A and 870B in Figure 8F). Current may be provided to conductor 114 by electrical leads 872 (shown as leads 872A and 872B in Figure 8F), which may be
10 coupled to a source of electrical power. Alternatively, electrical contact with conductor 114 may be provided via conductive material (such as metal) deposited, sputtered, or otherwise placed on hinge 870. In various embodiments cantilever 112 may be made of a reflective material (such as dielectric film, polycrystalline silicon, metal, non-metals or the like), since reactions to magnetic fields may be provided by conductor 114 rather than through a
15 magnetically sensitive material in cantilever 112. In various embodiments magnet 102 provides a magnetic field H_0 , which may be provided perpendicular to substrate 104 or at any oblique angle, as described above in conjunction with Figure 8E.

Actuation of reflector 800 may be accomplished by, for example, energizing conductor 114 with a current that produces a magnetic dipole moment (M) that may be
20 perpendicular to the plane of conductor 114. The magnetic dipole moment (M) may interact with the external magnetic field supplied (H_0) to produce a torque (T) on cantilever 112 such that $T = M \times H_0$. The torque (T) may be controlled to switch cantilever 112 between an "up" state and a "down" state, as described above. A more detailed description of this principle used in a different context is presented in Chang Liu, T. Tsao, Y-C Tai and C-M Ho,
25 "Surface Micro-machined Magnetic Actuators", MEMS '94, Oiso, Japan, pp. 57-62 (1994), incorporated herein by reference.

Figures 9A and 9B are side and top views, respectively, of an exemplary switch 900 that includes two type I mirrors 700A and 700B and one type II mirror/reflector 800. The axis of mirror 800 may be rotated 45 degrees (or to any other angle) from the axes of mirrors
30 700A and 700B as best seen in Figure 9B. An optional reflective layer 902 (such as a mirror) may be provided in various embodiments to reflect optical signals, as discussed more fully below. In various embodiments of the invention, an optical signal (such as a pulse or beam of light) 904 is to be switched to one of two outputs 910 and 920. In the first state of

switch 900 (shown in Figures 9A and 9B), cantilevers 112A and 112B of mirrors 700A and 700B may be placed in the "up" position so that optical signal 904 reflects off of reflective surface 702 (Figure 7), as shown. Reflective layer 902 suitably transmits optical signal 904 between mirror 700A and 700B, bypassing mirror 800 as appropriate, to output terminal 910.

Figures 10A and 10B are side and top views, respectively, of optical switch 900 in a second state (corresponding to output terminal 920). Cantilevers 112A of mirror 700A may be placed into the "down" state so that optical signal 904 is no longer reflected by reflective surface 702 of mirror 700A, but rather reflects off of the reflective surface of mirror 800, which may be oriented toward output terminal 920 as best seen in Figure 10B. Of course cantilever 112B of mirror 700B could also be placed into the "down" position, but such a transition may not be required since optical signal 904 does not reach mirror 700B in the state shown in Figure 10. Other embodiments of optical switches may exhibit different layouts. For example, a bi-directional switch may be fabricated by coating both sides of reflective portion 804 in mirror 800 with reflecting material.

Figure 11 is a top view of an exemplary 5 x 5 optical switch 950 that may be fabricated with switches 900 as described above. With reference to Figure 11, optical signals 904A-E are received at inputs 930A-E, respectively. Each signal may be routed by switch 950 to a desired output 940A-E, as appropriate. In the exemplary switch 950 shown in the Figure, input i1 is routed to output o3, input i2 is routed to output o1, input i3 is routed to output o4, input i4 is routed to output o5, and input i5 is routed to output o2. Of course any M x N switch fabric could be formulated, where M represents the number of inputs, N represents the number of outputs, and M and N are each integers. For example, 1 x 4 switches, 4 x 8 switches, 8 x 16 switches, 2 x 2 switches, or any other switch fabric could be formulated by adjusting the number of switches 700 and 800.

With continued reference to Figure 11, an exemplary 5 x 5 optical switch may include a matrix of twenty-five type II mirrors and eighty type I mirrors. The type II mirrors (shown as diagonal rectangles) may be arranged such that each input 930 has a type II mirror corresponding to each output 940. The type I mirrors (shown as smaller rectangles) are arranged as appropriate to deflect optical signals 904 around the type II mirrors as desired by reflecting the signals off of reflective layer 902 (not shown in Figure 11, but shown in Figure 9A). To route signal i5 to output o2, for example, type I mirrors 751 and 752 may be placed into the "up" state to deflect signal i5 around mirror 851. Type I mirrors 753 and 754 may

be placed into the "down" position to allow signal i5 to deflect off of type II mirror 852 toward output 940B. As described above, the various type I mirrors may be held in the "up" or "down" states by a magnetic field generated by a magnet 102. The various mirrors may be switched between states by generating appropriate magnetic pulses via a conductor 114 (Figure 7) or electrostatic pulses via electrodes 602/604 (Figure 6) to create a torque that moves the appropriate cantilever 112 to create the desired state for the desired mirror.

Optical Cross Switch Arrays

The performance, efficiency and overall effectiveness of an optical switch array as described above may be enhanced in various embodiments with the addition of signal-confining channels. Such channels may be placed around the various light paths within the switch to confine light to a desired path. Figure 12A provides a perspective view of an exemplary optical cross switch array 1200 including optical signal-confining channels. Although a switch array having a 2x2 fabric (i.e. two inputs and two outputs) is shown for simplicity, the techniques described herein may be readily extended to switches of any size NxM, wherein both N and M are any integer. Indeed, the use of signal-confining channels may enable switch fabrics much greater than previously though possible, such as fabrics on the order of 512 x 512, 1024 x 1024, or greater.

With reference to Figure 12A, optical signals 904A and 904B are incident from input optical fibers 1210A and 1210B and collimated through lenses 1220A and 1220B, respectively, before being switched onto output optical fibers 1210C-D. Optical mirrors 1280A-D may be any type of mirror such as a "Type-I" or "Type-II" mirror as described above. Optical signal-confining channels 1230A and 1230B are any channels, passages or other paths capable of directing light signals toward an intended destination, as described more fully below. In an exemplary embodiment, channels 1230A and 1230B are formed as passages having walls 1240 (Figure 12B) coated with a metallic or other reflective surface such as Al, Au, Ag, Cr, or the like. Input signals 904A-B are deflected by optical mirrors 1280A-D as appropriate so that the signal is deflected into a desired optical signal-confining channel 1230A-B toward an intended output path on either optical fiber 1210C or fiber 1210D. When optical signal 904 comes out of the optical fiber core 1210A-B, it goes through a micro lens 1220A or 1220B, respectively. The optical signal 904 is then collimated and propagates forward until it reaches the correct optical mirror 1280 for reflection into the appropriate optical signal-confining channel 1230 coated with high

reflectivity surface 1240. Lens 1220 is shown in Figure 12A as being separate from optical fiber 1210, but it could also be conveniently fabricated directly on the optical fiber by melting a portion of the fiber end, forming an epoxy drop on the fiber end and hardening, or any other method.

5 Signal-confining channels 1230 may be formed in a substrate or in any layer deposited upon the substrate with any technique. In an exemplary embodiment, channels 1230 are formed by dicing, sawing, micro-machining or otherwise forming a groove in the substrate, coating the groove with a reflective material, and then placing a reflective covering over the groove to form a channel as appropriate. The covering may be affixed to
10 the substrate with any form of adhesive such as epoxy or the like. Alternatively, channels 1230 may be micro-machined into the substrate, a layer of polyimide (or any other material) or any other layer using conventional micro-machining techniques. A thin-film of reflective coating may then be evaporated or otherwise placed in the channels 1230 and an additional cover layer may be deposited, sputtered or otherwise placed on top of channels 1230. As
15 briefly noted above, the inside walls of optical signal-confining channel 1230 are coated with high reflectivity material such as thin gold film, silver film, aluminum film, chrome film, or multi-layer of reflecting films, etc. so as to form reflective surface 1240. Metal films could be deposited by means of sputtering, e-beam evaporation, or any other technique. Channel 1230 section size varies widely from embodiment to embodiment based
20 upon, for example, different types of optical fiber 1210 and micro lens 1220, micro lens size, fiber core size, numerical fiber aperture, and the like. In an exemplary embodiment, however, the channel dimensions are on the order of about 100 microns wide and about 30-50 microns deep.

Figures 12(b) and (c) are cross-sectional views of two exemplary embodiments of
25 optical signal-confining channel 1230. In Figure 12(b), optical signal 904 is deflected into channel 1230 by a reflective mirror 1280, as described above. Signal 904 is reflected by reflective surface 1240 coating the sidewalls of channel 1230 such that signal 904 propagates toward the output. It will be appreciated that when optical mirror 1280 is in the closed position, it covers the opening of optical signal-confining channel 1230, thus allowing other
30 signals to propagate in channel 1230. An additional mirror 1284, for example, remains in a closed position as signal 904 from mirror 1280 enters the channel. Optical mirrors 1280, 1282, and 1284 may be actuated by various means (i.e., magnetic, electrostatic, piezoelectric, etc.), including through the techniques described hereinabove. For example, if

the mirror is coated with nickel, permalloy, iron or other soft magnetic material, the mirror may be actuated by a planar coil wrapped around the mirror (as discussed above for optical mirrors 700 and 800). Alternatively, the various mirrors may be activated by any kind of mechanism and can be activated by scratch drive, comb drive, impact comb drive, sliding gear with comb drive, simple electrostatic force between the mirror as one electrode and the other opposite non-movable electrode, or the like.

Alternate embodiments of channel/mirror arrangements are shown in Figures 13, 14 and 15. Figure 13 is a perspective view of an arrangement similar to that shown in Figure 12(a) wherein an input optical signal 904 is deflected into channel 1230 by mirror 1280, which is positioned at an angle alpha with respect to the top of the channel. Various embodiments will select different values for angle alpha so that light is directed into channel 1230. In an exemplary embodiment, angle alpha may be between 30 and 60 degrees, such as about 45 degrees. Figures 14(a) and (b) are top and side views, respectively, showing an exemplary lateral orientation of mirror 1280. In the embodiment shown in the Figure, mirror 1280 is positioned at approximately 135 degrees from the channel to direct signal 904 at an approximately right angle into channel 1230. As shown in Figure 14, mirror 1230 is at a first state wherein light is reflected toward end 1401 of channel 1230. In this state, mirror 1230 may be positioned at an angle beta that is less than about 135 degrees (or any other appropriate angle) such that light is reflected as desired. With reference now to Figure 15, mirror 1230 may be placed in a second state such that that the angle beta between the mirror and the channel is greater than 135 degrees (or any other appropriate angle) to deflect light toward the opposite end (i.e. end 1402) of channel 1230. Of course the exact angles used will vary depending on the exact arrangement of input light with respect to channel 1230, and may vary widely from embodiment to embodiment.

Reflectivity in channel 1230 may vary depending upon such factors as material-type and the surface smoothness of channel 1230. In an exemplary embodiment, reflectivity may vary from about 80% to 90%. From standard optical calculations, it can be easily found that after many instances of reflection, the optical signal intensity attenuates exponentially. For example, if the reflectivity is 0.9, after 10 times of reflection, the intensity is reduced to 0.35 of its original value. After 50 times, intensity drops to 0.05; after 100 instances, intensity drops to 0.000027.

With momentary reference again to Figure 12(c), an optional second optical mirror 1282 (also referred to as a "channel mirror") may be rotably placed in the bottom of optical

signal-confining channel 1230 beneath upper optical mirror 1280 to alter the direction of the optical signal 904 and to thereby lessen the reflection of optical signal 904 in channel 1230. Mirror 1282 (such as those discussed above and in reference to optical mirrors 700 or 800 in applications using micromagnetic actuation) may be fabricated under the top mirror 1280 such that mirror 1282 is rotatably attached to the bottom surface of optical signal-confining channel 1230. When both top and bottom mirrors are activated (by any means selected in accordance with each specific design), the desired scenario is the outgoing optical signal 904 is reflected by the bottom small mirror 1280 and then travels along channel 1230 long axis of symmetry. Noting that in the practical case, due to limitation in processing, mirrors 1280 do not function with exactly 100% precision, thus causing optical signal propagation direction to deviate slightly from the channel long axis depending on the processing. Nevertheless, by employing the methods and devices disclosed by the present invention, the magnitude of reflection can be greatly reduced. For example, if there is no deviation, no reflection would be encountered after optical signal 904 reflects from the bottom mirror. If the deviation is 1 degree, for a 5cm long, 20 μ m wide and 20 μ m high channel, the expected number of reflections is about 43. If the deviation is 0.5 degree, the number is 22. If it is 0.1 degree, the number is 4, etc. Hence the intensity loss is greatly lessened, particularly in large systems such as 512 \times 512 or even larger matrices. Figures 16 and 17 show exemplary first and second states, respectively, for directing an input light signal 904 into channel 1230. As shown in the Figures, channel mirror 1282 may be positioned at an angle that is a function of the angle of top mirror 1280 such that light is directed toward either end 1401 (Figure 17) or end 1402 (Figure 16) as desired. In the embodiment shown, mirror 1282 is positioned at an angle of 180-beta to direct light toward end 1402 and at an angle of beta-90 to direct light toward end 1401. Of course the exact angles and formulas used may vary from embodiment to embodiment.

In an alternate embodiment, incident optical signal alignment may be improved through the use of additional channels 1230. With reference now to Figures 18 and 19, channels 1230i may be used to guide the input optical signal 904. For simplicity, only one optical signal trace is shown in the Figure, although it will be appreciated that channels could be formed for any number of input signals 904. To reduce the number of reflections in channel 1230, however, additional bottom mirrors 1282 may be added under the top mirrors that are not shown in Figures 18 and 19.

It will be appreciated that because optical signal 904 is guided by channel 1230, the increase of array number does not raise alignment problems. Moreover, optical cross switch array 1200 designs are not limited by the optical fiber types. Both single mode fiber and multimode fiber can be used for the device. Again referring to Figure 12A, although the figure illustrates incident optical signal direction as being perpendicular to channel 1230, so as to guide the outgoing optical signal, switch 1200 does not necessarily have to be configured in this way. The angle between the incident optical signal direction and outgoing channel can be designed to be any angle in accordance with optical cross switch array application. Further, channel 1230 does not necessarily have to be rectangular as shown, but may be appropriately configured in any shape such as round, oval etc. Additionally, channel 1230 does not necessarily have to be straight. It can also be curved, zigzagged, etc, as long as it can propagate the optical signal 904 inside channel 1230. Further, the channel guides disclosed herein may be useful in devices other than optical switches. In particular, optical channel guides may be useful in any optical device or component such as a switch, router, connector, waveguide, relay, input or output terminal, header, optical transmitter or receiver, or the like.

The corresponding structures, materials, acts and equivalents of all elements in the claims below are intended to include any structure, material or acts for performing the functions in combination with other claimed elements as specifically claimed. Moreover, the steps recited in any method claims may be executed in any order. The scope of the invention should be determined by the appended claims and their legal equivalents, rather than by the examples given above. Finally, it should be emphasized that none of the elements or components described above are essential or critical to the practice of the invention, except as specifically noted herein.

CLAIMS

1. A device for transmitting optical signals, said device comprising:
an optical input accepting said optical signals;
5 a control device directing said optical signals between said at least one optical input
and an optical output; and
a channel located between said optical input and said optical output confining said
optical signals to a pre-determined path.
- 10 2. The device of claim 1 wherein said control device comprises at least one mirror
element configured to reflect said optical signals within said device.
3. The device of claim 2 wherein each of said at least one mirror elements comprises a
cantilever having a magnetically sensitive portion and a reflective portion.
- 15 4. The device of claim 3 wherein said cantilever is configured to be switched between a
first state and a second state by one of a plurality of electromagnetic signals.
5. The device of claim 4 wherein each of said electromagnetic signals are configured to
20 induce a torque in one of said cantilevers corresponding to one of said plurality of
mirror elements, such that said cantilever is switched between said first state and said
second state.
6. The device of claim 5 wherein said plurality of electromagnetic signals comprise
25 magnetic signals generated by a plurality of conductors.
7. The device of claim 5 wherein said plurality of electromagnetic signals comprise
electrostatic signals generated by a plurality of electrodes.
- 30 8. The device of claim 1 wherein said channel comprises at least one reflective wall.
9. The device of claim 8 wherein said reflective material comprises one of the group
consisting of aluminum, gold, silver and chromium.

10. The device of claim 5 wherein said channel comprises at least one reflective wall.

11. The device of claim 10 wherein said reflective material comprises one of the group
5 consisting of aluminum, gold, silver and chromium.

12. The device of claim 8 wherein said channel comprises at least one channel mirror
configured to receive said optical signal and to direct said optical signal through said
channel.

13. The device of claim 10 wherein said channel comprises at least one channel mirror in
optical communication with one of said mirror elements, wherein said channel mirror
is configured to receive said optical signal and to direct said optical signal through
said channel.

14. A method of switching an optical signal between a first output and a second output,
the method comprising the steps of:

providing a switching element comprising a cantilever having a reflective portion;
and

switching said cantilever such that said reflective portion is placed the path of said
20 optical signal when said optical signal is desired at said first output, and such
that said reflective portion is placed out of the path of said optical signal
when said optical signal is desired at said second output.

15. The method of claim 14 further comprising the step of conducting said optical signal
25 through a channel, wherein said channel comprises a reflective wall.

16. The method of claim 15 wherein said conducting step comprises directing said
optical signal away from said reflective wall with a channel mirror.

17. The method of claim 15 wherein said cantilever is configured to be switched by one
30 of a plurality of electromagnetic signals.

18. The method of claim 17 wherein said electromagnetic signals produce a magnetic torque in said cantilever.
19. A switch configured to execute the method of claim 15.
20. A switch configured to execute the method of claim 18.

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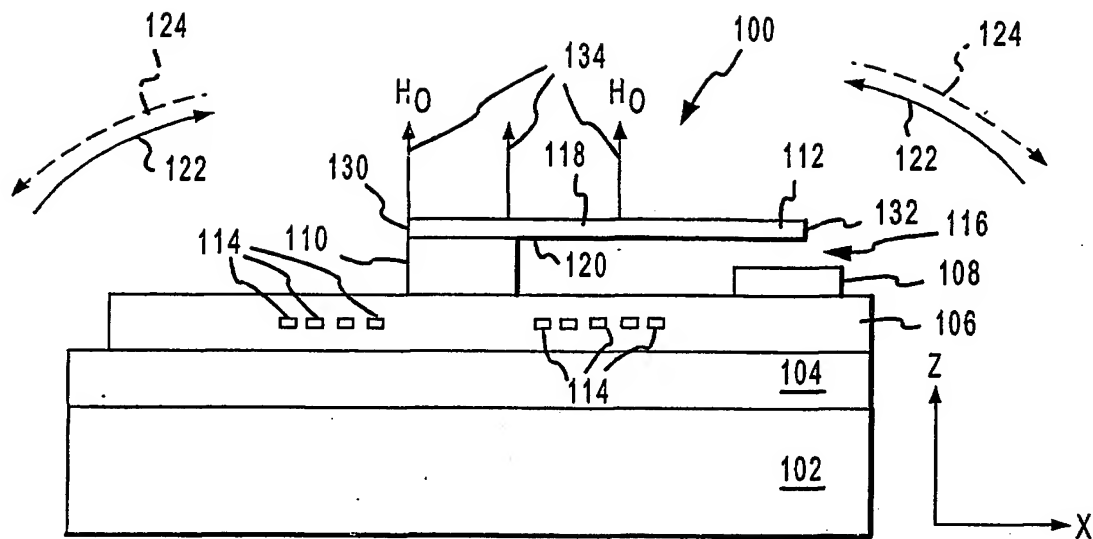


FIG. 1A

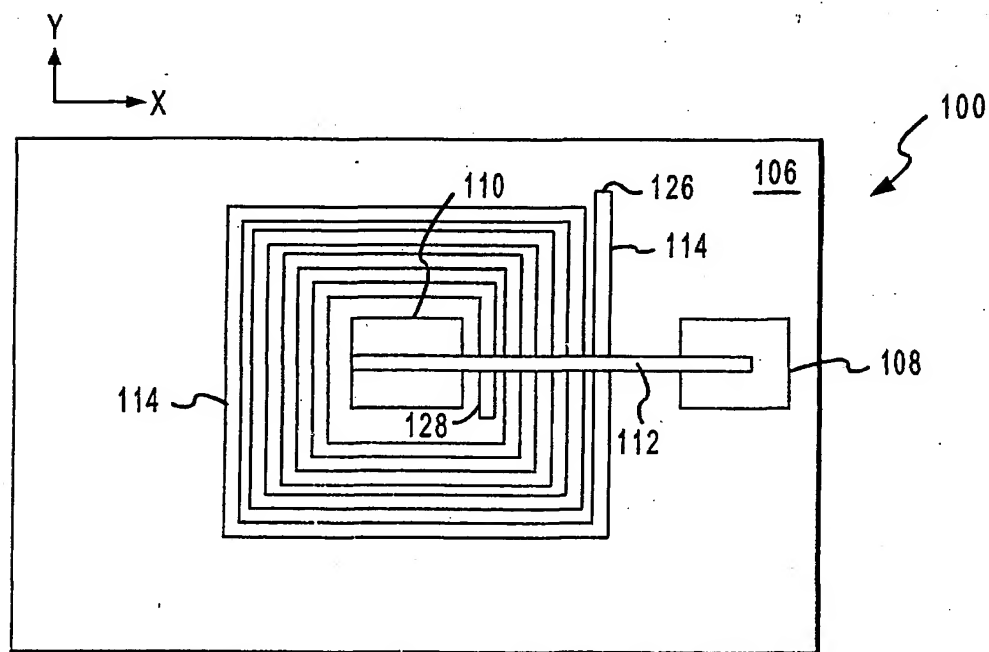


FIG. 1B

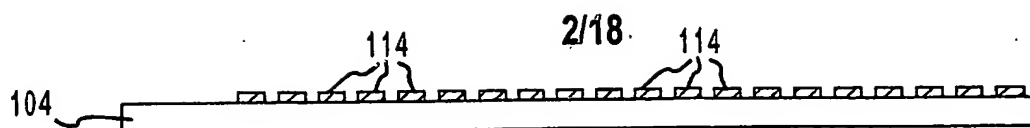


FIG. 2A

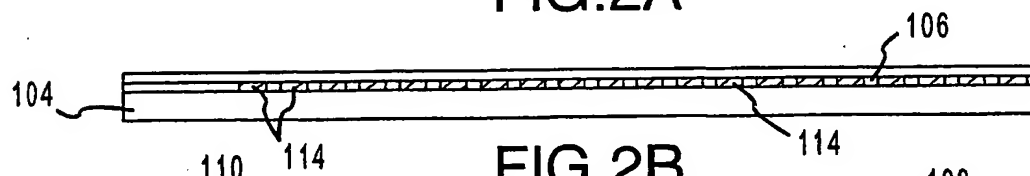


FIG. 2B

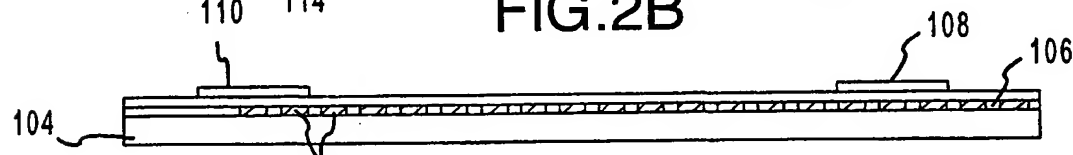


FIG. 2C

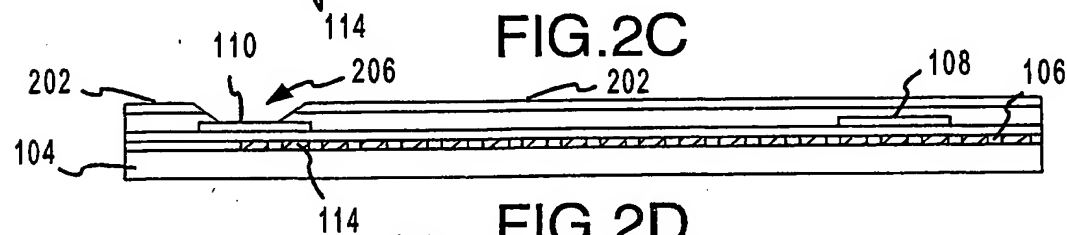


FIG. 2D

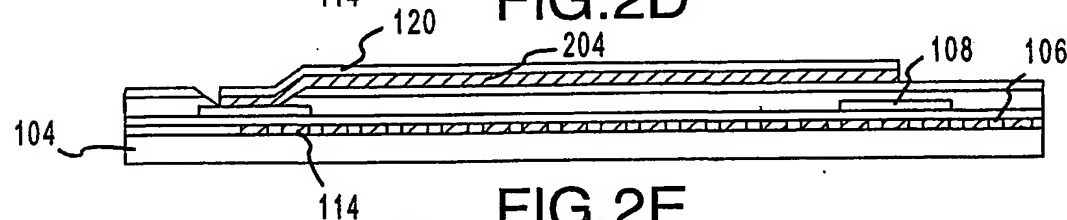


FIG. 2E

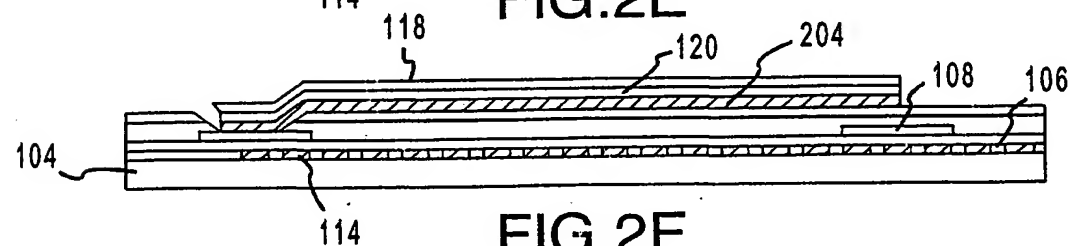


FIG. 2F

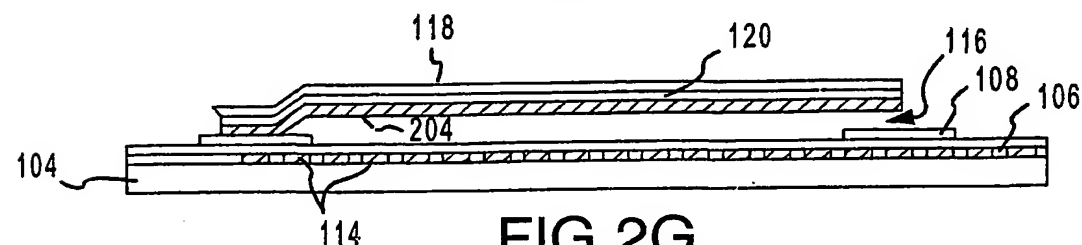


FIG. 2G

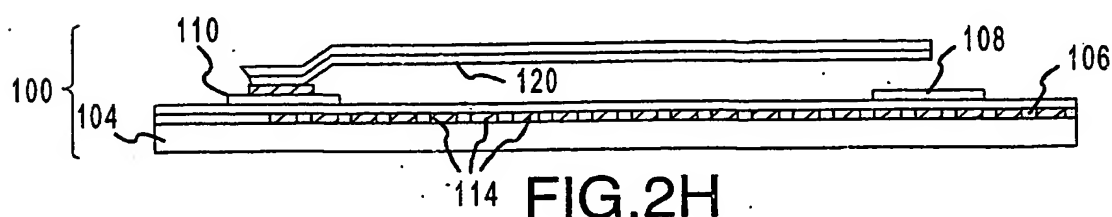


FIG. 2H

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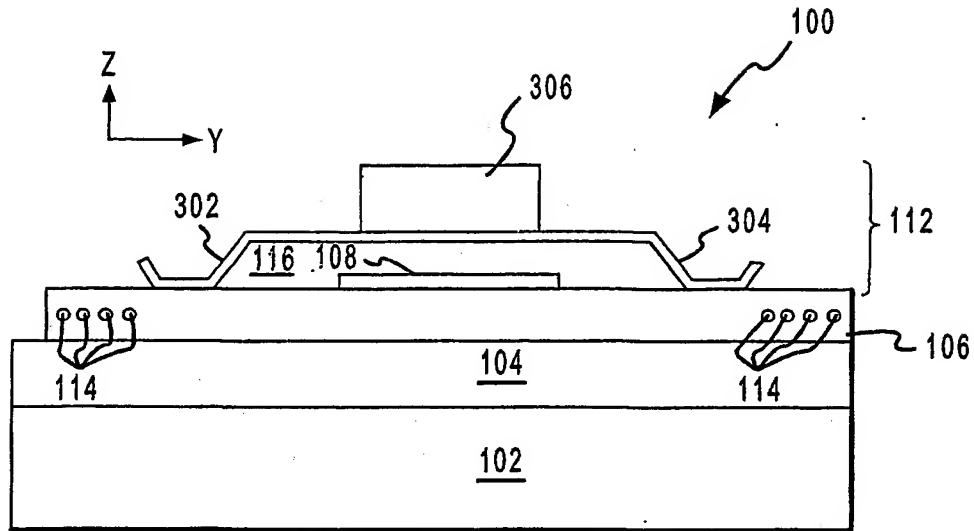


FIG. 3A

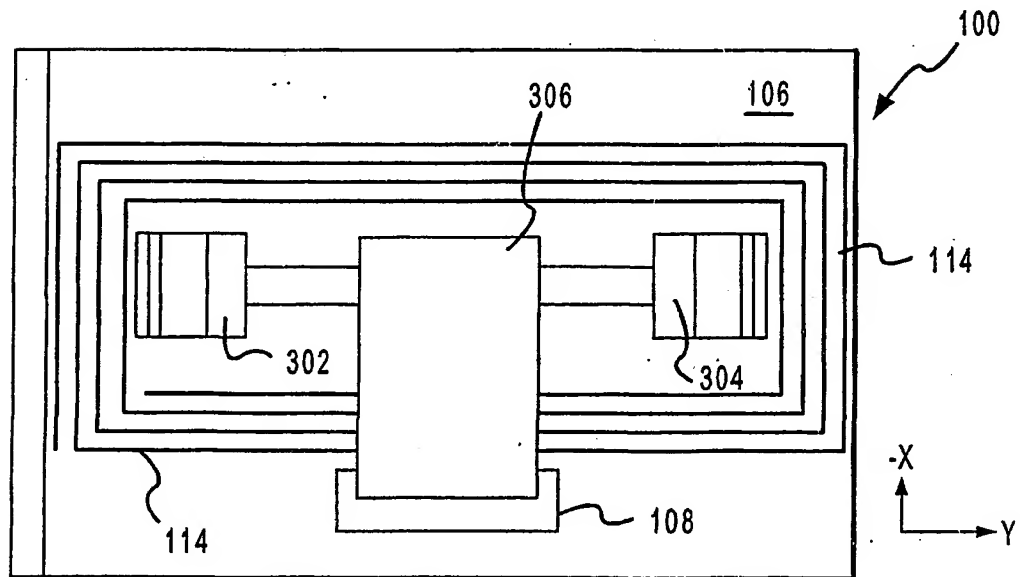


FIG. 3B

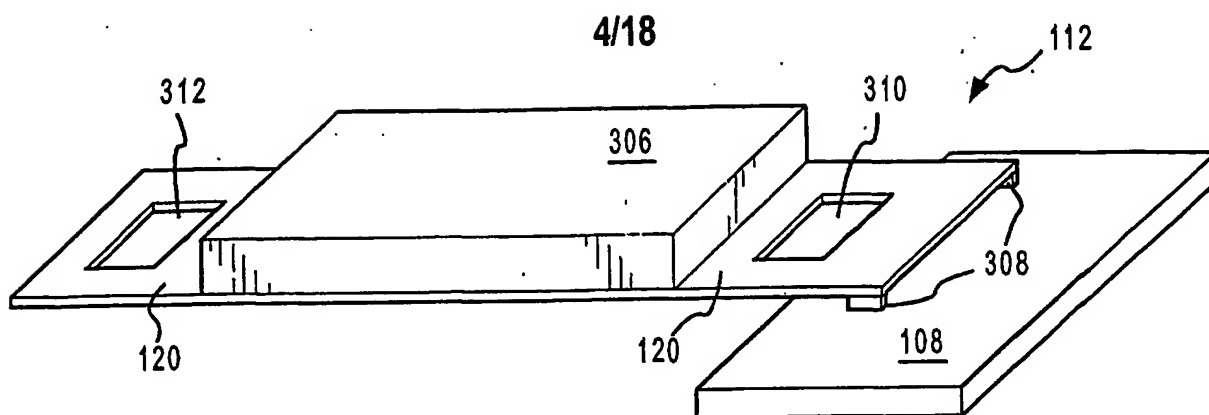


FIG.3C

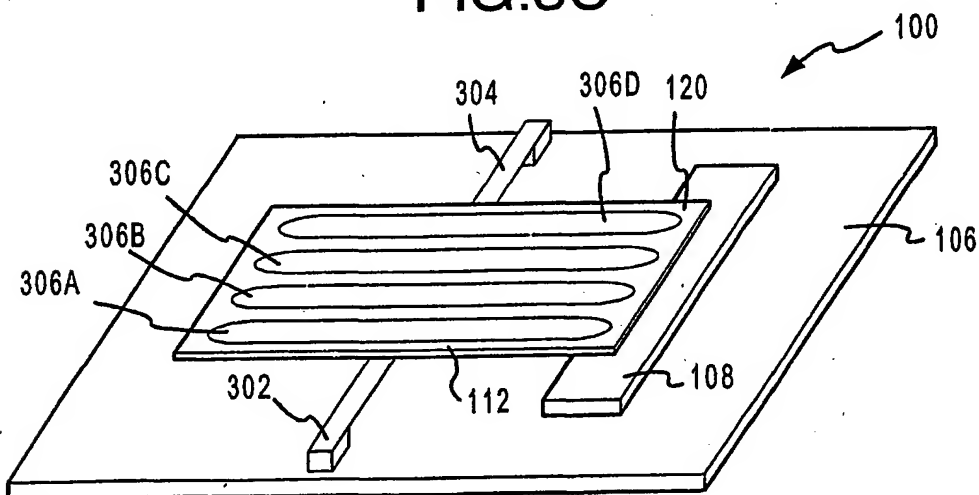


FIG.3D

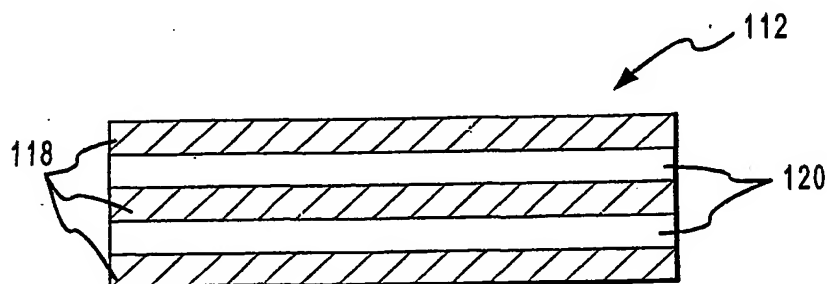


FIG.3E

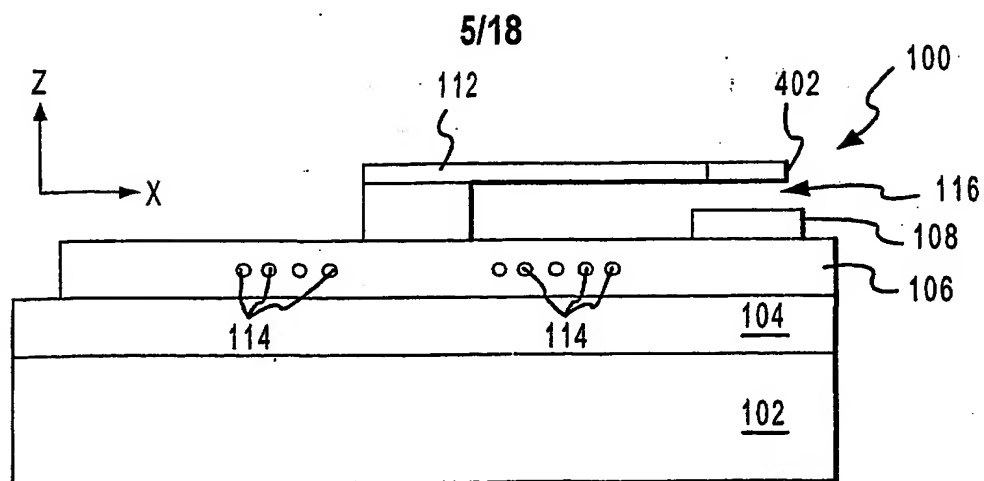


FIG. 4A

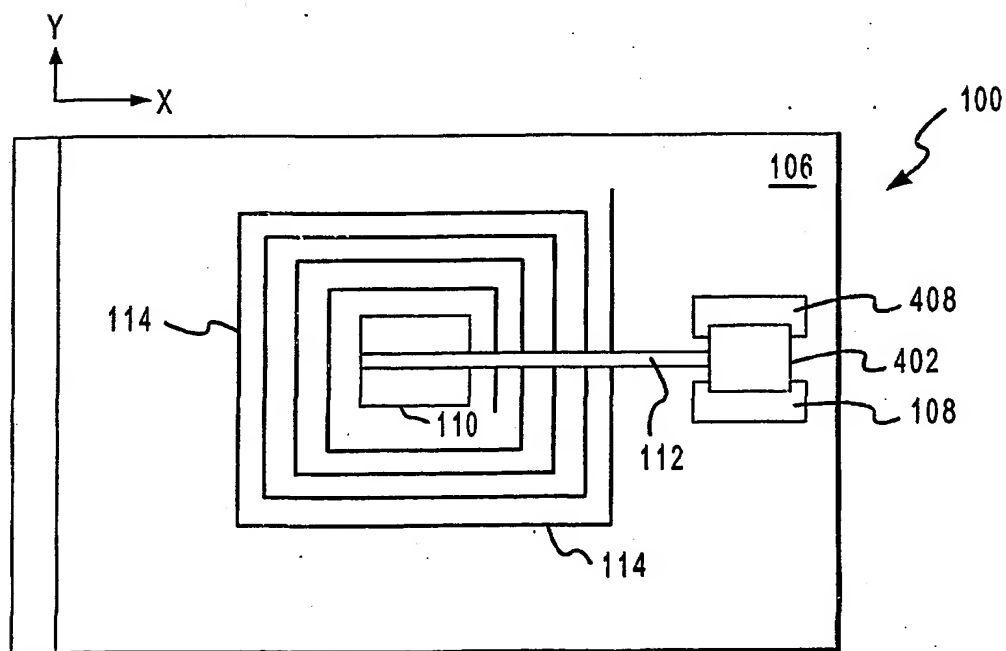


FIG. 4B

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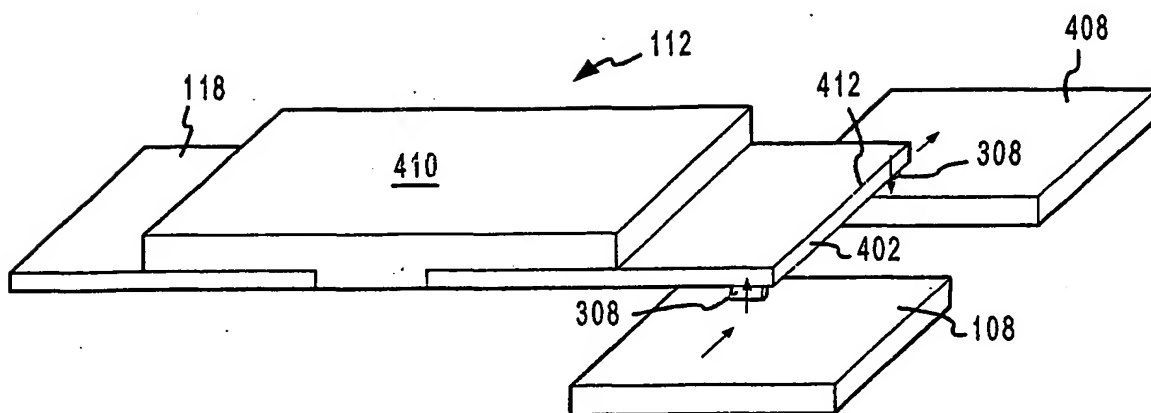


FIG. 4C

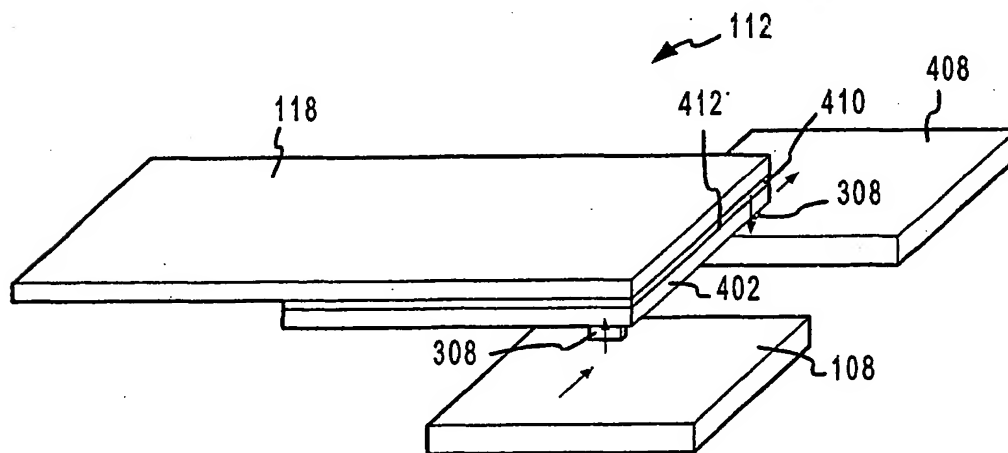


FIG. 4D

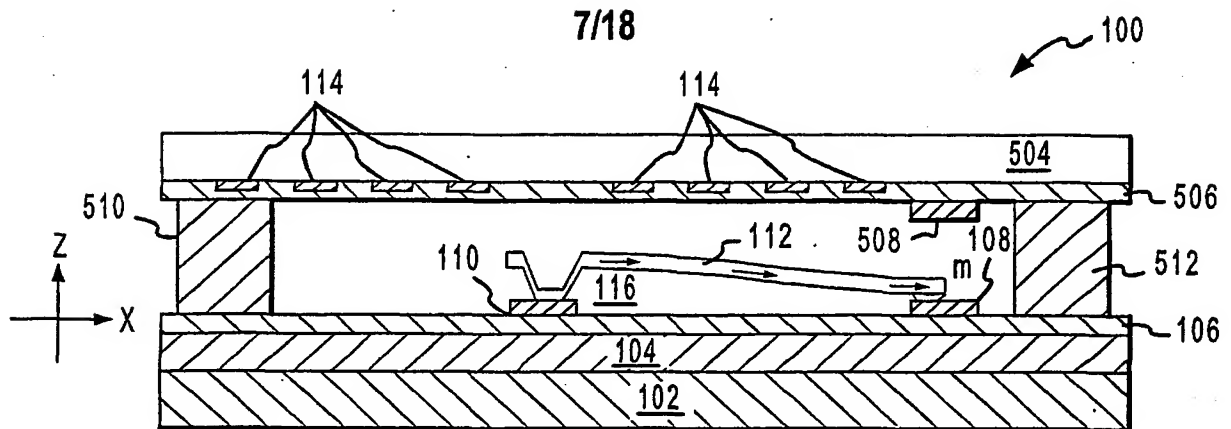


FIG.5

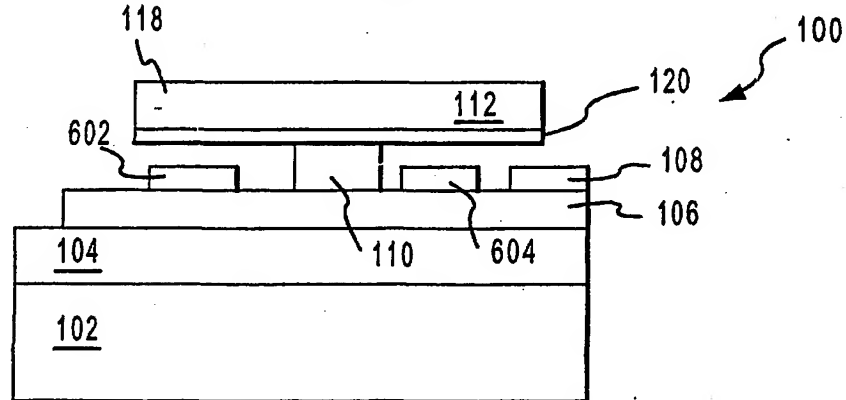


FIG.6A

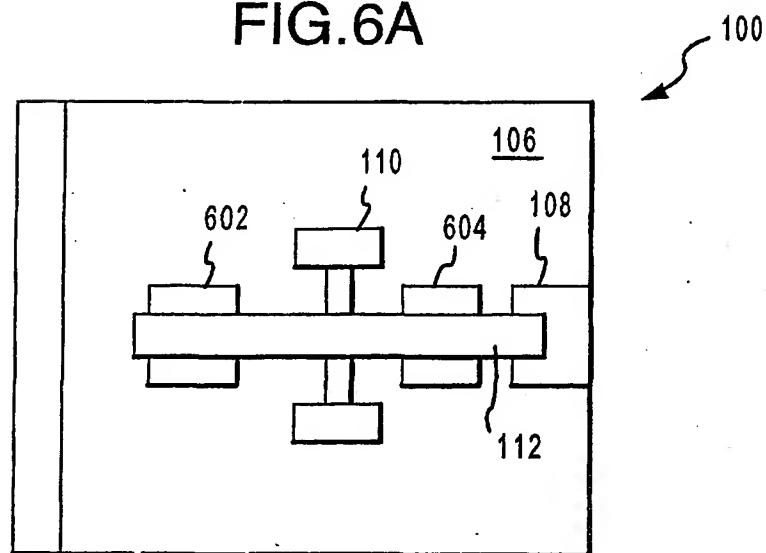


FIG.6B

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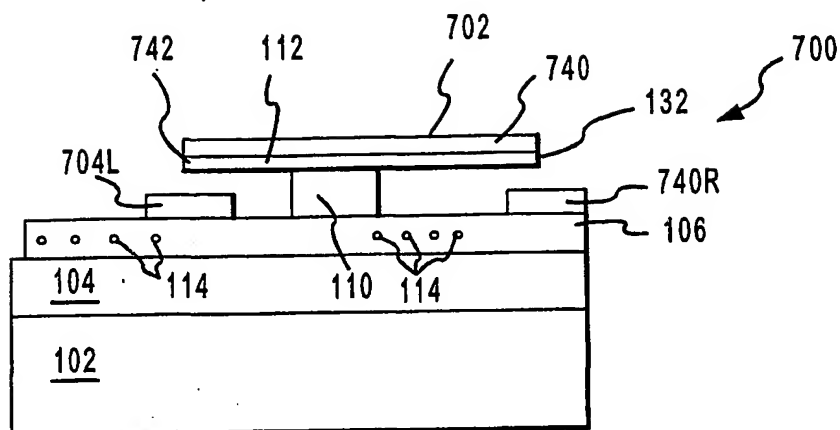


FIG. 7A

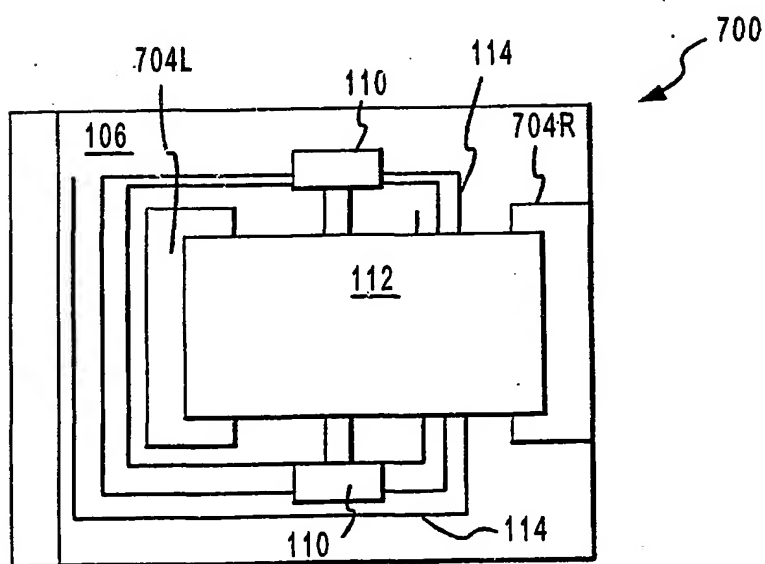


FIG. 7B

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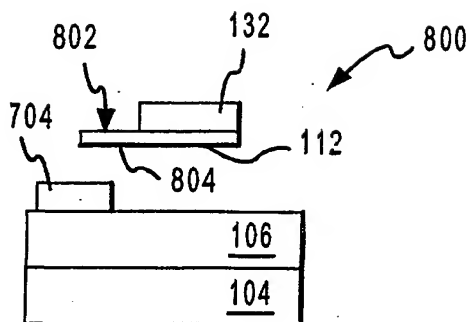


FIG. 8A

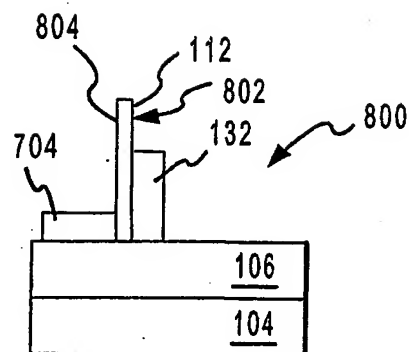


FIG. 8C

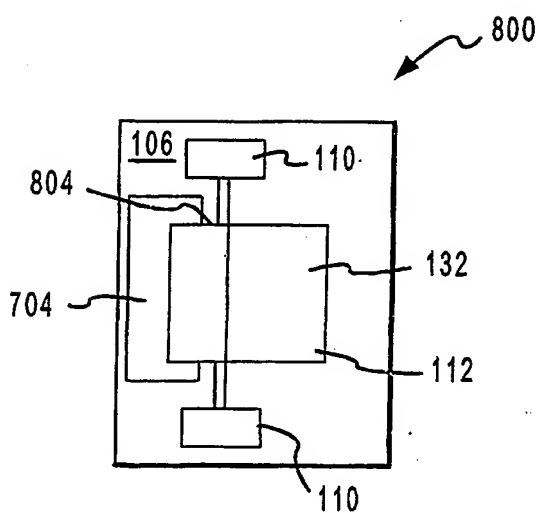


FIG. 8B

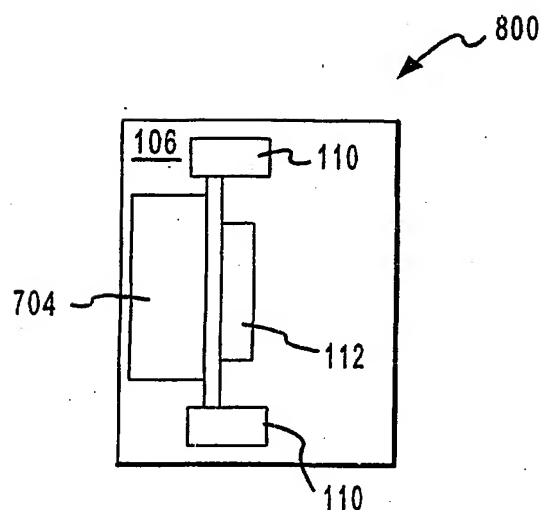


FIG. 8D

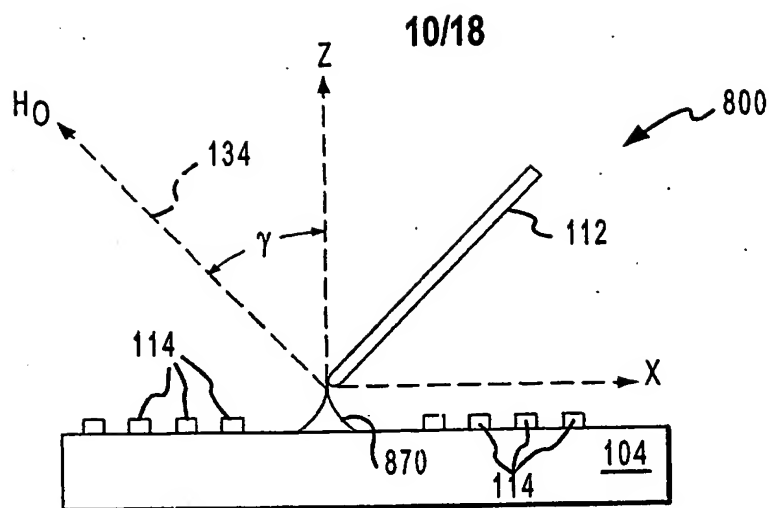


FIG. 8E

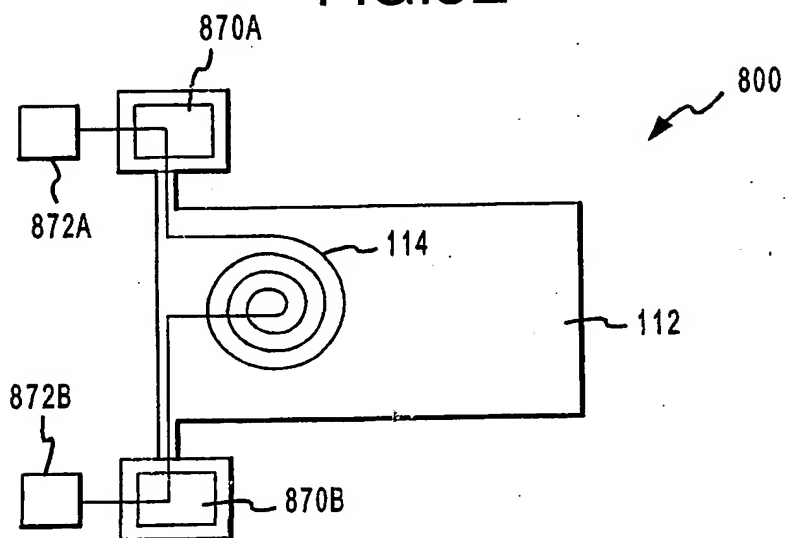


FIG. 8F

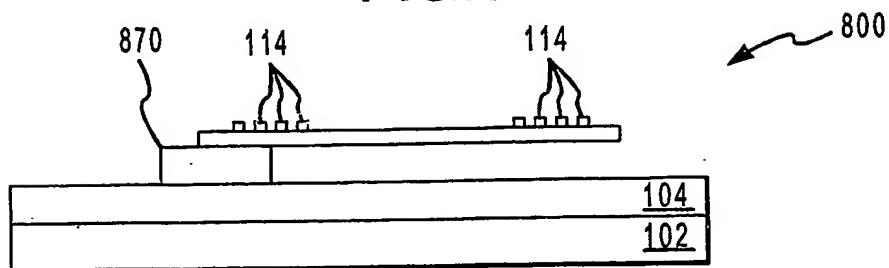


FIG. 8G

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FIG. 9A

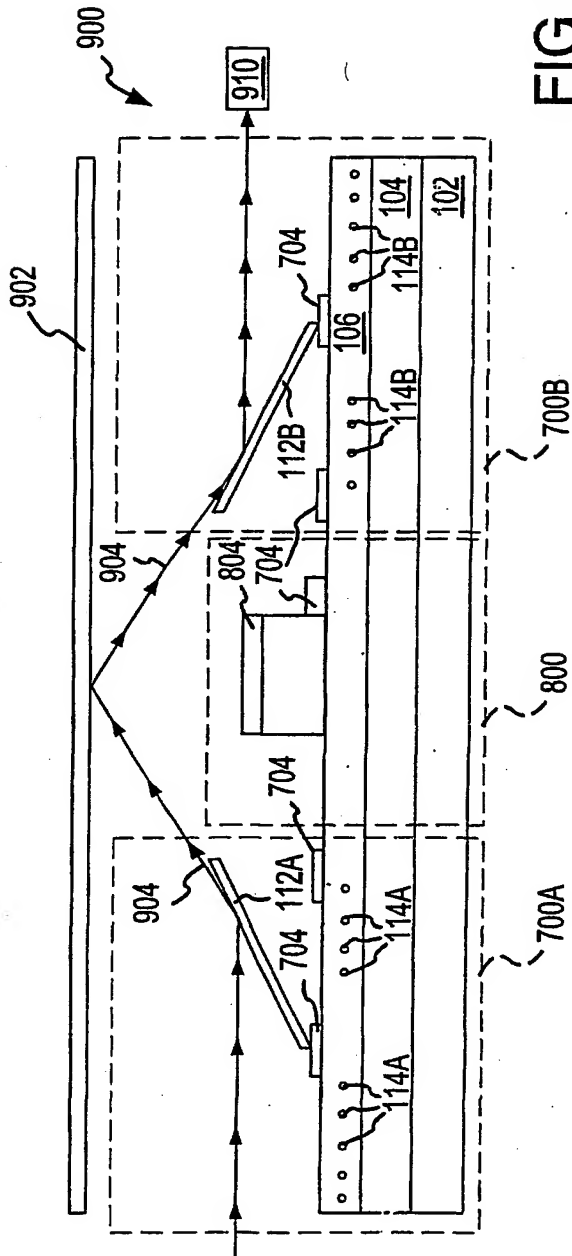
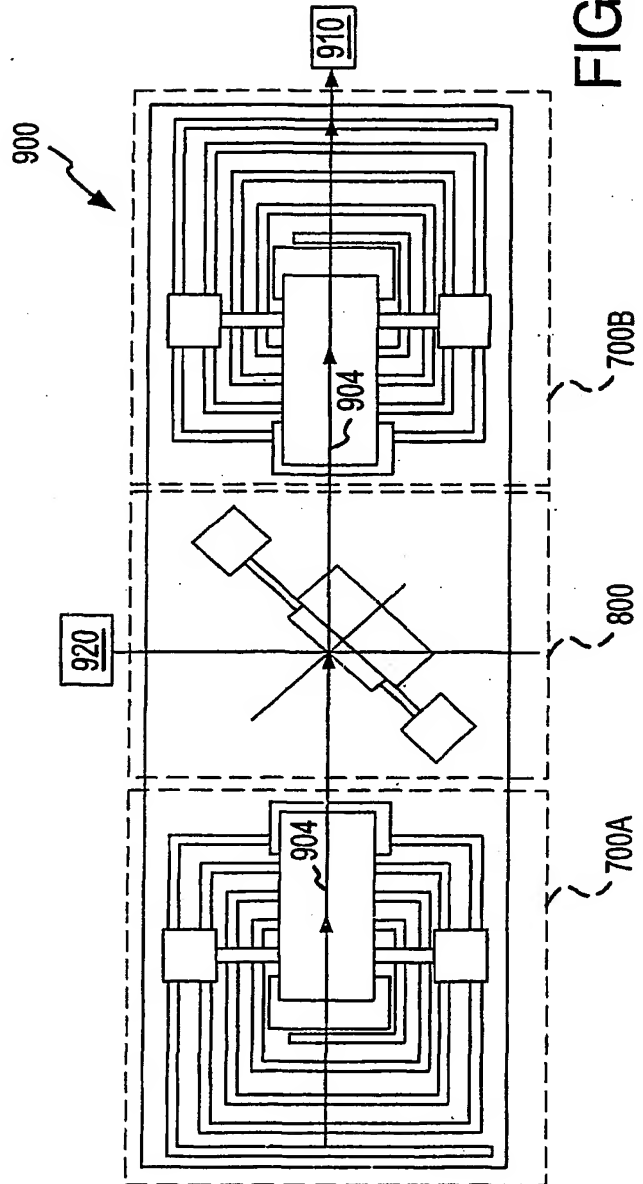
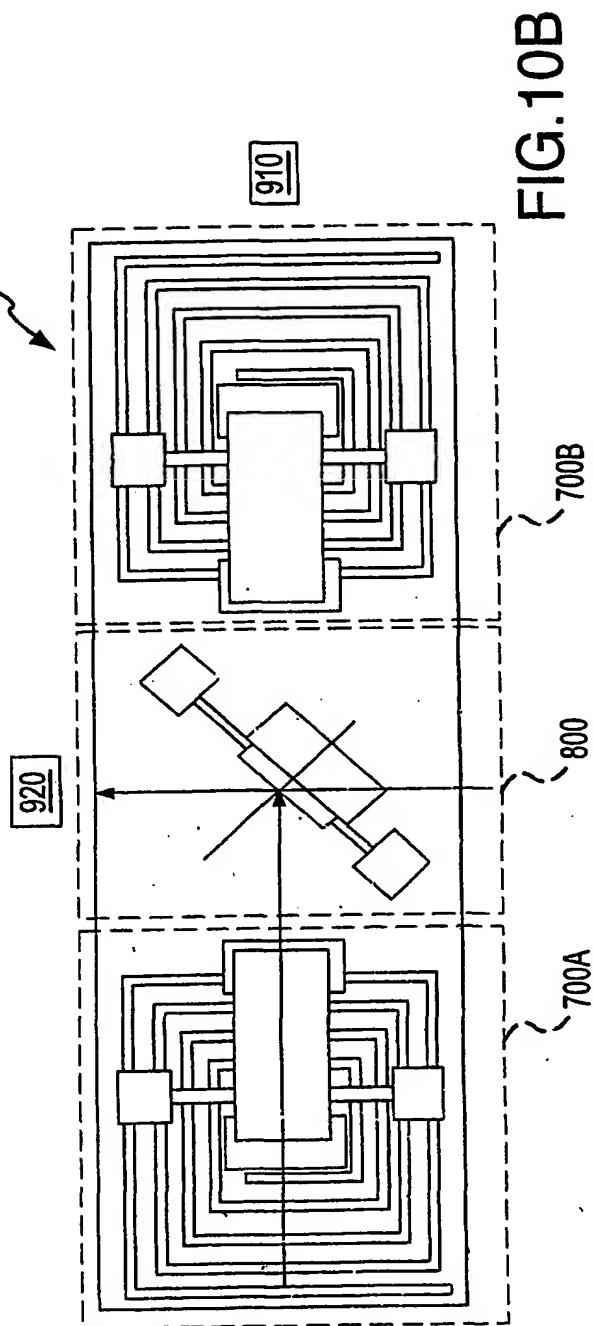
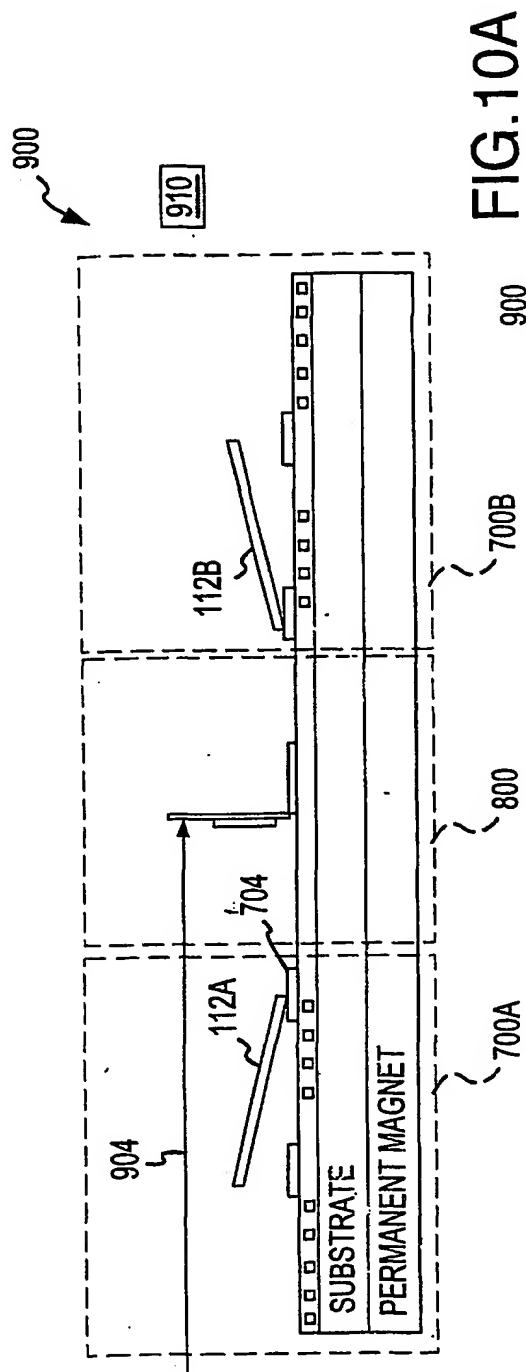


FIG. 9B



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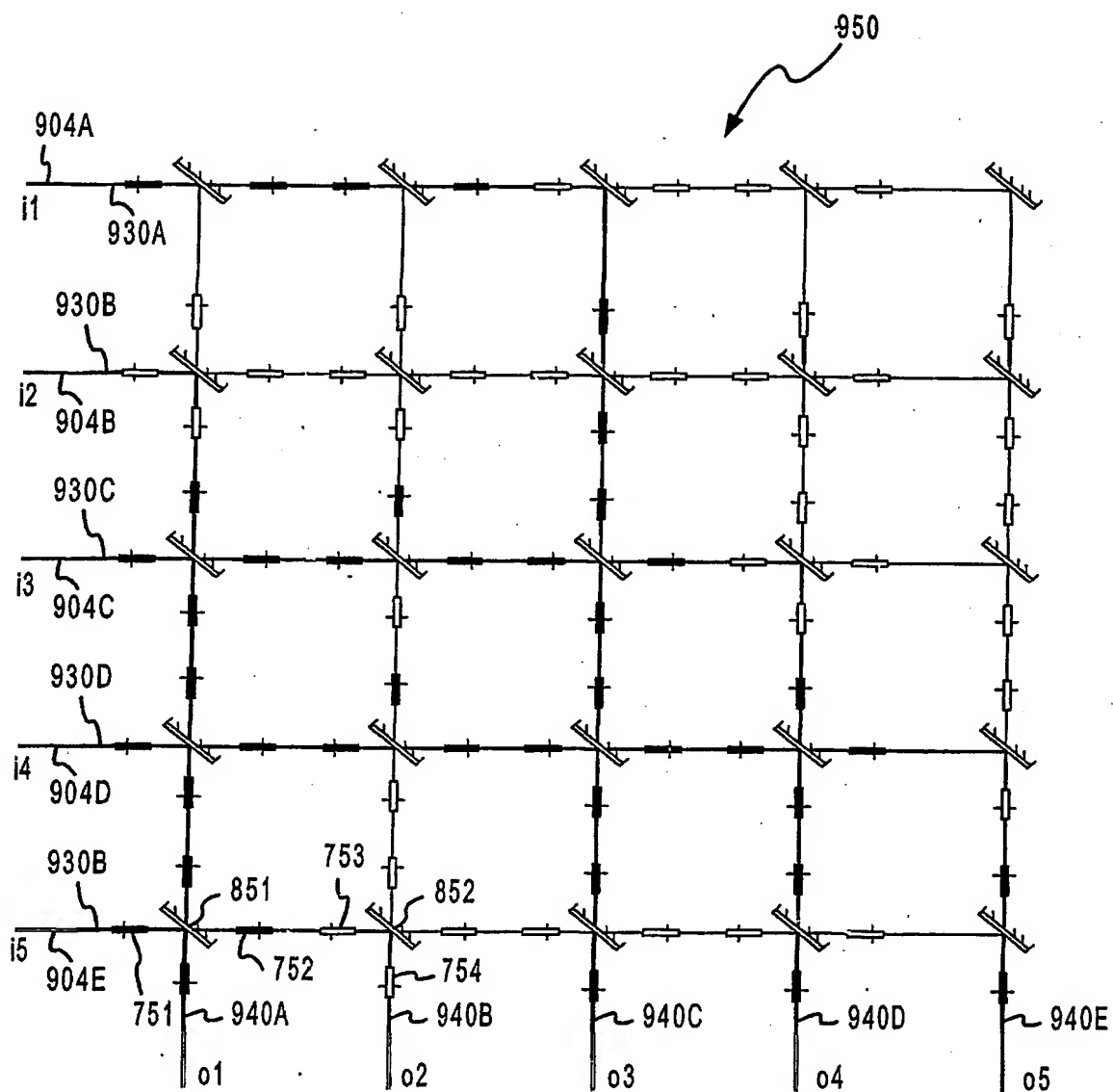


FIG. 11

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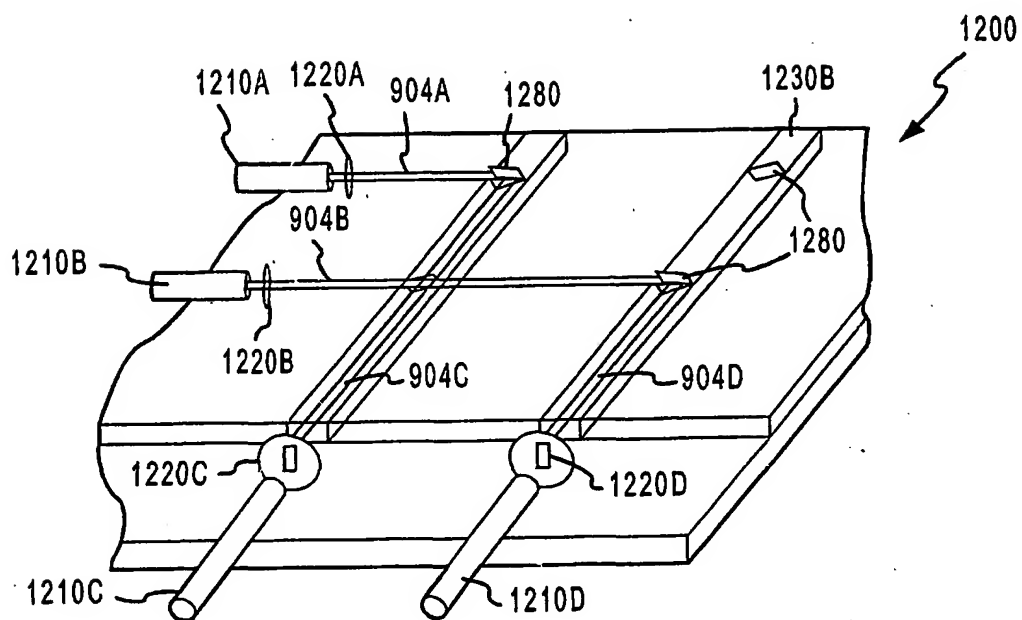


FIG. 12A

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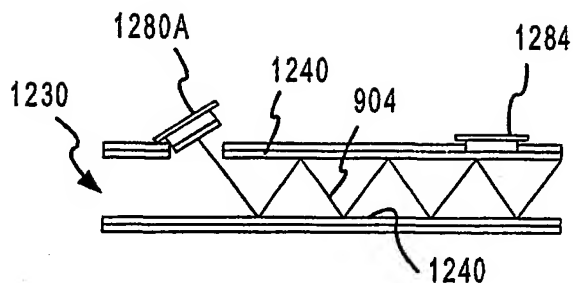


FIG. 12B

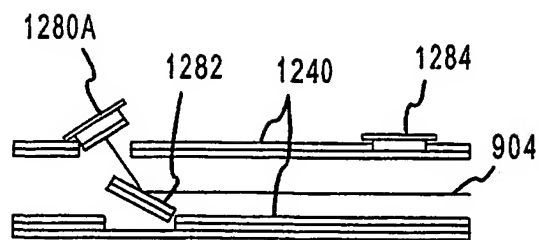


FIG. 12C

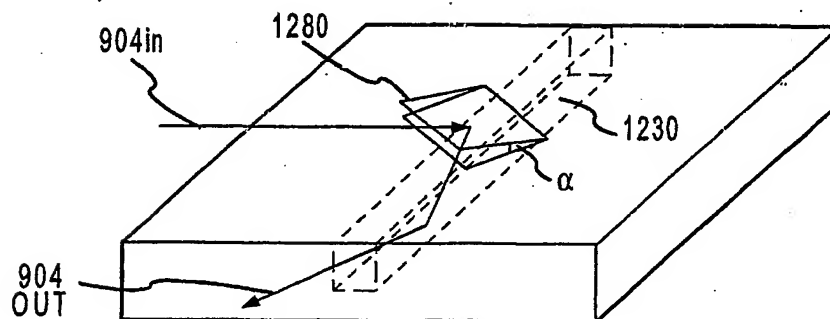


FIG. 13

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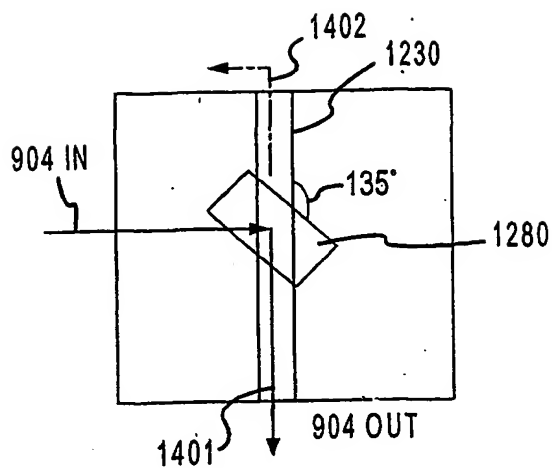


FIG. 14A

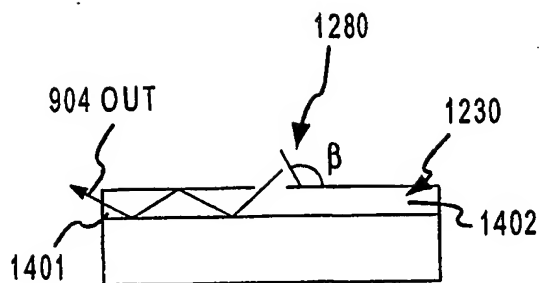


FIG. 14B

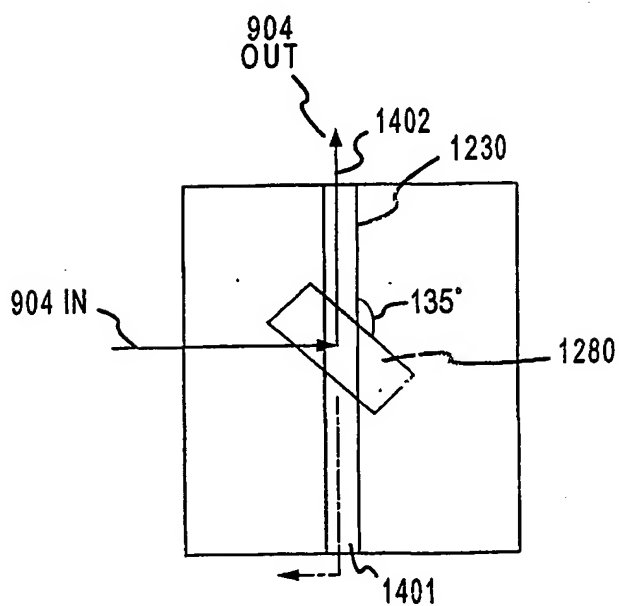


FIG. 15

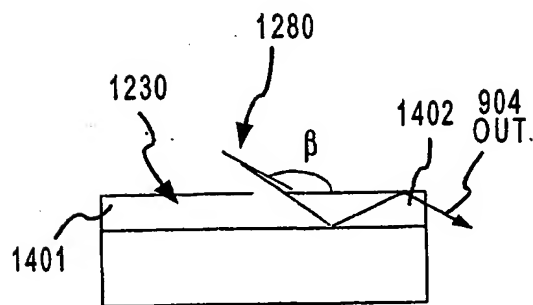


FIG. 15B

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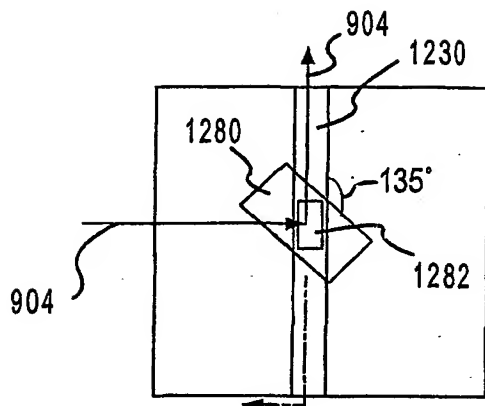


FIG. 16A

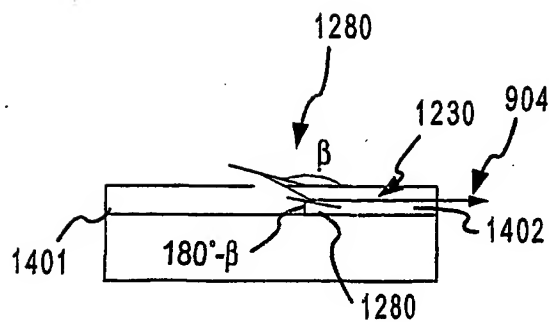


FIG. 16B

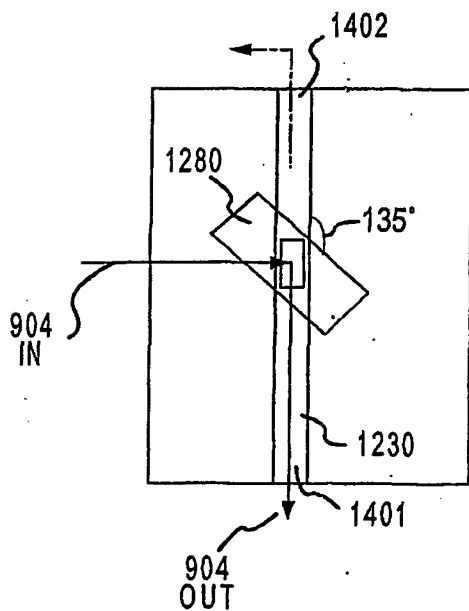


FIG. 17A

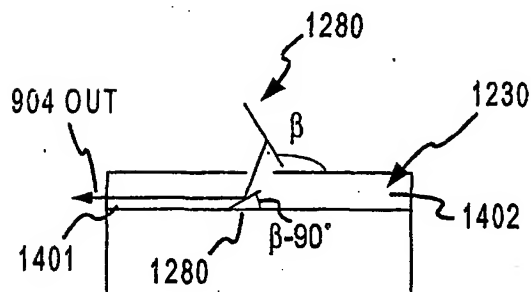


FIG. 17B

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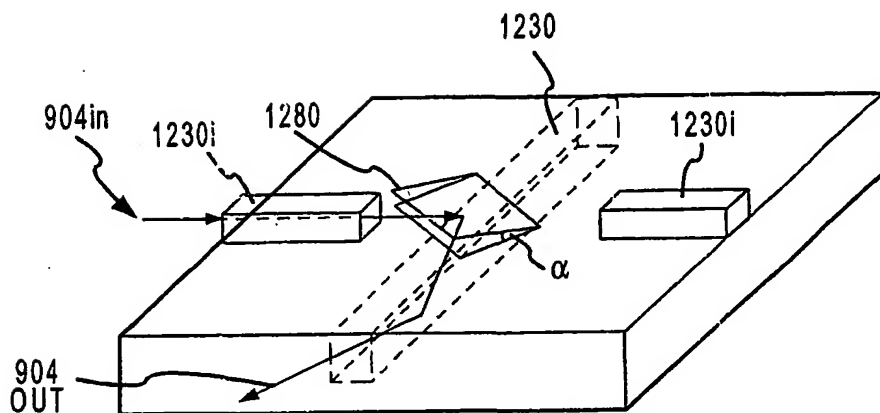


FIG.18

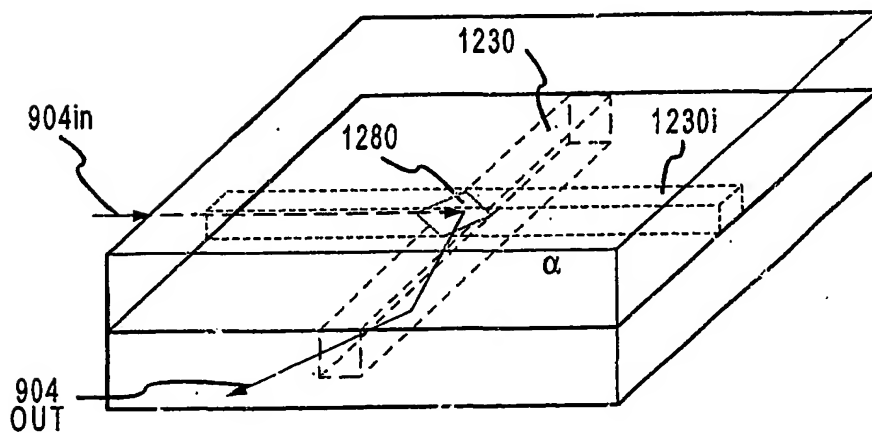


FIG.19

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(22) International Filing Date: **11 July 2001 (11.07.2001)**

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(26) Publication Language: **English**

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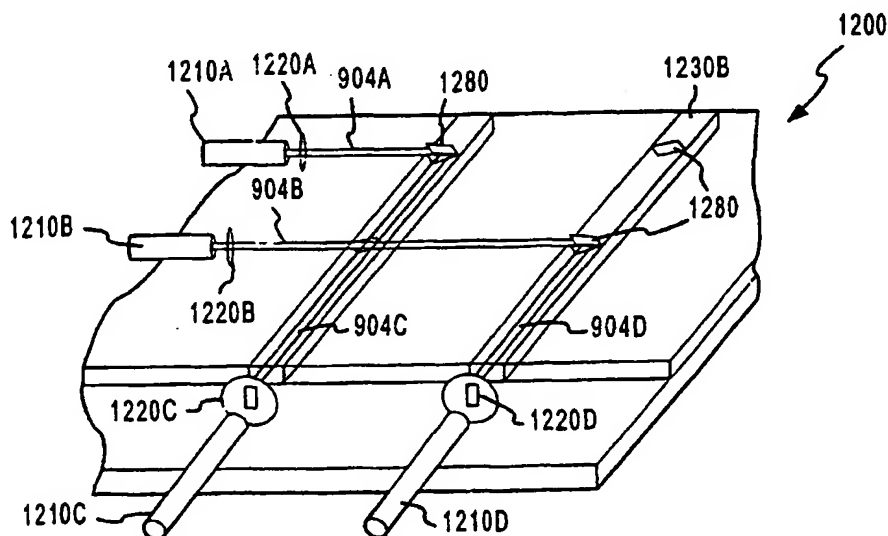
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AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,
CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,
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(84) Designated States (*regional*): ARIPO patent (GH, GM,
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Published:
— with international search report

[Continued on next page]

(54) Title: **OPTICAL MEMS SWITCHING ARRAY WITH EMBEDDED BEAM-CONFINING CHANNELS AND METHOD OF OPERATING SAME**



(57) Abstract: A new optical switch device and method of operating such a device overcomes alignment problems through the use of an optical signal-confining channel that may be embedded so as to confine optical signals in a desired propagation path such that the optical signal's alignment with the output is secured. Small-angle mirrors may be used so as to direct the optical signal into the intended optical signal-confining channels so as to achieve the desired optical switching. The mirrors could be latching micro-mirrors or non-latching micro-mirrors. Such mirrors could be controlled by electrostatic actuation, thermal actuation or electromagnetic actuation, or any other technique.



(88) Date of publication of the international search report:
27 June 2002

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

INTERNATIONAL SEARCH REPORT

Internal Application No

PCT/US 01/21856

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G02B26/08 G02B26/02 G02B6/35

According to International Patent Classification (IPC) or to both national classification and IPC

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Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CHEN R T ET AL: "A HIGH-SPEED LOW-VOLTAGE STRESS-INDUCED MICROMACHINED 2 X 2 OPTICALSWITCH" IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE INC. NEW YORK, US, vol. 11, no. 11, November 1999 (1999-11), pages 1396-1398, XP000893775 ISSN: 1041-1135	1,2,8, 14,15, 17,19
A	page 1396, right-hand column -page 1397, left-hand column	3-7
X	US 4 496 211 A (DANIEL MAURICE) 29 January 1985 (1985-01-29) column 16, line 5 - line 22 column 20, line 1 - line 40; figure 16 -/--	1,2,8,9, 12, 14-16,19

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Date of mailing of the international search report

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P,X	US 6 094 293 A (OTA HITOSHI ET AL) 25 July 2000 (2000-07-25) column 6, line 43 -column 7, line 67; figures 2,13 column 12, line 27 - line 45 X & JP 2000 098270 A 7 April 2000 (2000-04-07) ---	1-6,14
X	US 5 048 912 A (KUNIKANE TATSURO ET AL) 17 September 1991 (1991-09-17) figure 2 ---	1,8,12
A	EP 0 452 012 A (AMERICAN TELEPHONE & TELEGRAPH) 16 October 1991 (1991-10-16) column 3, line 40 -column 4, line 37; figures 1-4 -----	3-6

INTERNATIONAL SEARCH REPORT

Information on patent family members

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PCT/US 01/21856

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